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Reliability Assessment at Airline Inspection Facilities, Volume II: Protocol for an Eddy Current Inspection Reliability Experiment

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16. Abstract

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The Aging Aircraft NDI Development and Demonstration Center (AANC) at Sandia National Laboratories is charged by the FAA to support technology transfer, technology assessment, and technology validation. A key task facing the center is to establish a consistent and systematic methodology to assess the reliability of inspections through field experiments. This task is divided into three major areas: reliability of eddy current lap splice inspections at transport aircraft maintenance facilities, reliability of inspection at commuter aircraft maintenance facilities, and reliability of inspection associated with visual inspection of aircraft structural parts.

Volume II is the second document in a series of three describing the planning, execution, and results of an eddy current inspection field experiment. This document provides a detailed description of the experimental hardware and protocols. It also describes the methodology to be used in the analysis of the data.

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PREFACE

In August 1991, a major center with emphasis on validation of nondestructive inspection (NDI) techniques for aging aircraft was established at Sandia National Laboratories (SNL) by the Federal Aviation Administration (FAA). This center is called the Aging Aircraft NDI Development and Demonstration Center (AANC). The FAA Interagency Agreement, which established this center, provided the following summary tasking statement: "The task assignments will call for Sandia to support technology transfer, technology assessment, technology validation, data correlation, and automation adaptation as on-going processes." Key to accomplishing this tasking is the FAA/AANC Validation Center, which will reside in a hangar leased from the City of Albuquerque at the Albuquerque International Airport.

As one of its first projects AANC established a working group consisting of personnel from Sandia, Science Applications International Corporation (SAIC), and AEA Technology. The working group was charged with designing and implementing an experiment to quantify the reliability associated with airline eddy current inspections of lap splice joints.

The result of AANC's efforts is this three volume document, Reliability Assessment at Airline Inspection Facilities which details an experimental concept for inspection reliability assessment and a specific experiment designed to determine probability of detection (POD) curves associated with eddy current inspections. The experimental concept and eddy current experiment take into account human factor influences, which have not been fully addressed in past POD work. The result will be a better quantification of the reliability of the inspection techniques currently employed in the field. This will lead to better inputs for damage tolerance analysis and improved confidence in the specification of inspection intervals.

Because the FAA/AANC NDI Validation Center has been tasked to pursue other related NDI reliability experiments, the protocol for this experiment was developed first as a generic protocol then as a specific eddy current lap splice inspection protocol. The generic protocol is presented in Vol I: A Generic Protocol for Inspection Reliability Experiments, and the specific eddy current experiment protocol is presented in Vol II: Protocol for an Eddy Current Inspection Reliability Experiment. Because of the extent and duration of the experiment, the actual results of the experiment are presented separately in a third volume, Vol III: Results of an Eddy Current Inspection Reliability Experiment.

The experiment proposed in this Volume will not only result in realistic POD curves for the eddy current inspection of lap splices, but will also address a fundamental element in the long term goals of the FAA/AANC NDI Validation Center. Inspection validation includes the independent and quantitative evaluation of the effectiveness and reliability of an inspection methodology. The realism of the evaluation depends upon the extent to which the influences of inspection environments and other human factor conditions are incorporated. The full-scale test bed in a hangar environment that is being established with the FAA/AANC NDI Validation Center will be a major step in allowing realistic evaluations to take place. A missing ingredient, however, is the variation induced into the measurement process because of the differences in environmental and management conditions that exist between facilities. The facility variation quantified from the lap splice experiment will thus provide data that can be used in future validation efforts.

ACKNOWLEDGMENTS

This proposal is the result of the cooperative efforts of many people within Sandia National Laboratories (SNL), Science Applications International Corporation (SAIC), and AEA Technology. The working group members coordinating activities within these organizations were:

Giancarlo Borgonovi	SAIC
Dennis Roach	SNL
Don Schurman	SAIC
Ron Smith	AEA Technology
Floyd Spencer	SNL

Chris Smith, FAA Technical Center, and Pat Walter of Sandia provided extensive assistance to the working group.

As presented, the overall experimental plan represents the decisions and deliberations of the Probability of Detection working group. As such, the group accepts all responsibility for the work. However, the experimental planning was not done in isolation and benefited greatly from interactions with others familiar with reliability assessment work in the airline industry. Specifically, the following people provided review and input into the groups' planning: David Broek, FractuREsearch, Inc.; Sam Sampath and Chris Seher, FAA Technical Center; Steve LaRiviere and Mike Hutchinson, Boeing; Chuck Annis and Ed Donahue, Pratt & Whitney; Robert Blanchard, Civil Aeromedical Institute; Chris Bhagat, Wright Patterson AFB; Richard Burkel and Richard Graman, GE Aircraft Engines; John Petru, Air Force NDI Program Office; Ward Rummel, Martin Marietta; Dave Lotterer, Air Transport Association; Sarah McLeod, Aeronautical Repair Station Association.

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NOMENCLATURE

a, flaw size	Physical dimension of a flaw used in POD analysis models, usually a crack length.
AANC	Aging Aircraft NDI Development and Demonstration Center run by Sandia National Laboratories for the Federal Aviation Administration
AD	Airworthiness Directive
ANOVA	Analysis of Variance, a statistical procedure for comparing the variability between groups to the variability within groups.
α, β	Intercept and slope coefficients used in logistic regression equation. Other forms of the regresion equation may be parameterized by μ and σ, the mean and standard deviation.
baseline	Set of measurements performed under laboratory conditions on a given set of flaw specimens.
dress rehearsal	Inspection tasks performed according to established protocols for the purpose of testing, in a realistic environment, all the functions required in fielding a reliability assessment experiment.
ET	Eddy current testing
FAA	Federal Aviation Administration
false alarm	An NDI response of having detected a flaw but at an inspection location where no flaw exists.
inspector	Person who applies an NDI technique, interprets the results, and makes a judgment as to the presence or absence of a flaw.
lap splice joint	Area where different sections of the outer fuselage skin are joined. The joint is formed by one piece overlapping the other and has fasteners installed through the two layers of skin.
MANOVA	Multivariate Analysis of Variance, a statistical procedure that generalizes the analysis of variance to consider two or more dependent variables simultaneously.
monitor	Person tasked with observing and documenting the results of inspections performed during an NDI reliability assessment experiment.

NDI	Nondestructive inspection. Visual inspection is customarily excluded from being considered NDI.
NTSB	National Transportation Safety Board
POD, POD(a)	Probability of detection. As a function of flaw size, it is the fraction of flaws of nominal size, a, that is expected to be detected.
POFA	Probability of false alarm
protocols	Set of written procedures for conducting all activities related to the implementation of a reliability assessment program.
ROC	Receiver Operating Characteristic, a curve incorporating detection probabilities with probabilities of false alarms.
SAIC	Science Applications International Corporation
SID	Supplemental Inspection Documents,
SNL	Sandia National Laboratories

EXECUTIVE SUMMARY

This document presents the protocol for an experiment to assess the reliability of high-frequency eddy current inspections of lap splice joints in airline maintenance and inspection facilities. The protocol follows the guidelines set forth in "Reliability Assessment at Airline Inspection Facilities, Vol. I: A Generic Protocol for Inspection Reliability Experiments," DOT/FAA/CT-92/12,I.

Following the Aloha accident in April 1988, the National Transportation Safety Board stated: "There are human factor issues associated with visual and nondestructive inspection which can degrade inspector performance to the extent that theoretically detectable damage is overlooked." The goal of the proposed experiment is to provide a quantitative assessment of inspectors' performance in airline facility use of high-frequency eddy current inspection procedures. The "human factor issues" are thereby encompassed in the experiment.

Secondary objectives are established in an attempt to understand the factors that influence the reliability and to provide self-assessment with respect to the experimental plan. Specific factors that are to be studied within the experimental plan are (1) off-angle cracks, (2) unpainted versus painted surfaces, (3) variation of reference standards, (4) accessibility of task, (5) time into inspection (related to "boredom"), (6) work shifts, and (7) differences in specimen definition. During the course of the experiment, data will also be collected on conditions that exist at the facilities, such as lighting levels and other environmental factors. Data specific to the inspectors, such as level of training, experience level, and recentness of experience on the specific task, will also be collected.

Details are provided on the two types of test samples that provide the test vehicle. The experiment includes 36 specimens (20 by 20 inches) that are configured as a lap splice with specified flaw counts and flaw lengths. This represents 720 inspection sites (161 flawed) and an estimated time of 2 to 2.5 hours for each inspection. The experiment also includes two Foster-Miller panels (10 by 6 feet) that will contain all the structural components found on the aircraft fuselage. These panels contain 216 inspection sites and should take from 1 to 1.5 hours to inspect. Flaw orientations and densities will not be controlled on these panels, but a goal of 15 to 25 flaws per panel in the 0.04 to 0.20 inch has been established.

A baseline laboratory assessment will be conducted so that the total effect of moving from laboratory to field environments can be evaluated.

1. Introduction

This protocol details the procudures, hardware, and techniques used to field an experiment to quantify the reliability of high-frequency eddy current inspections of aircraft lap splice joints, as the inspections are performed in airline maintenance and inspection facilities. (A schematic of a lap splice joint in the outer skin of the aircraft fuselage is shown in Figure 2-1.) The presentation parallels the format established in "Reliability Assessment at Airline Inspection Facilities, Vol. I: A Generic Protocol for Inspection Reliability Experiments" [1].

1.1 Scope

The planned experiment is specific to inspection procedures used on Boeing 737 lap splice joints. Inspection procedures are given in Boeing Documents 737 D6-37239, part 6, subject 53-3-03 and 737 D6-37239, part 6, subject 53-3-05. Three inspection methods are covered: sliding probe, oversize template, and rotating surface probe. Both the sliding probe and the rotating surface probe procedures require that any flaw indication be checked with the oversize template method. The equipment needed for each of these methods varies. The sliding probe method requires an instrument capable of an impedance plane display. The oversize template method can be used with meter signal display instruments, and the rotating surface probe method requires an oscilloscope display.

Inspections of riveted joints using high-frequency eddy current technology are not unique to Boeing. Douglas and Airbus maintenance manuals require the same type of inspection using similar equipment. The results of the proposed experiment will be reflective of the technology as employed in field conditions and thus will be applicable beyond the single aircraft type chosen to provide definition for the test vehicle.

1.2 Background

Inspection of aging aircraft is a matter of national concern. Programs have been established by manufacturers, airline operators, and the Federal Aviation Administration (FAA) to address these concerns. Specifically, the FAA published requirements in 1981 directing the development of Supplemental Inspection Documents (SIDs). The intent of the SIDs is to extend routine maintenance programs in order to detect fatigue damage in older aircraft. High-frequency eddy current inspections are an integral part of both routine maintenance checks and SID directed checks for surface fatigue cracks.

In April 1988, an Aloha Airlines Boeing 737-200 experienced an explosive decompression and structural failure while en route to Honolulu, HI. Subsequent investigation indicated that a debond had occurred in a lap joint, followed by extensive fatigue cracking in adjacent rivet holes. Eddy current inspection of the upper row of rivets in the lap joint was required by an FAA Airworthiness Directive. Following the accident, the National Transportation Safety Board (NTSB) stated: "There are human factor issues associated with visual and nondestructive inspection which can degrade inspector performance to the extent that theoretically detectable damage is overlooked" [2].

Evaluations of the reliability of lap splice eddy current inspection procedures have been carried out [3]. The issue raised by the NTSB has not been addressed, however, as the existing evaluations have not addressed the impact of field conditions. The objective of the proposed experiment is to evaluate the reliability of eddy current inspection procedures as they are done routinely at airline maintenance and inspection facilities, thereby implicitly incorporating human factors issues into the evaluation.

1.3 Reliability Assessment Elements

Figure 1-1 is a flowchart showing various elements that are to be included in the lap splice experiment. These elements have been grouped into four major phases. They are:

- Experiment plan
- Field experiment implementation
- Data Analysis
- Reporting (Plan of Action)

Though each of these phases will be discussed individually in sections 2 through 5, the Plan of Action deserves some comment here. Early in the planning phase a decision was made maximize the productive dissemination of the results of this experiment. This, of course, would require the identification of correctable problems, but does not stop there. Interest groups must be identified and the character and quantity of information distributed must be tailored to these groups requirements. This function will require the concerted efforts of both the FAA Technical Center staff and AANC working group.

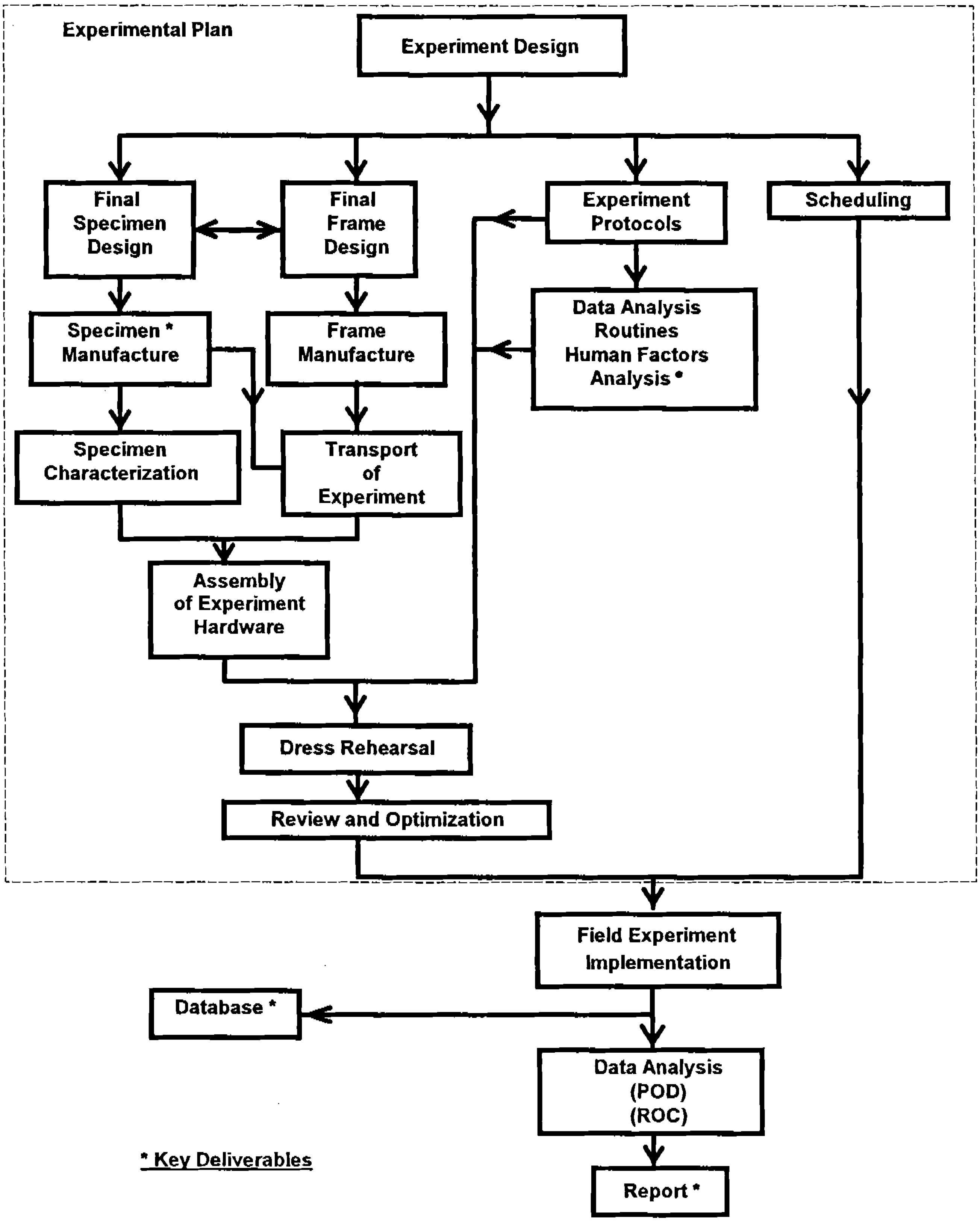


Figure 1 - 1. Reliability experiment outline.

2. Experimental Plan

The experimental plan provides a mechanism to assess the reliability of high-frequency eddy current inspections of lap splice joints as those inspections are performed in aircraft maintenance and inspection facilities. Facility differences in procedures, equipment, training, and environment are thus part of the system being studied. The experimental plan does not control these factors but calls for gathering relevant data. (For a discussion of controlled versus uncontrolled factors see Volume I: A Generic Protocol for Inspection Reliability Experiments.) The data gathered will be analyzed as potential explanatory factors for observed variations in inspection results.

2.1 Experimental Design

Various factors that can affect the inspection results are identified and discussed in Section 2.1.1. Experimental objectives that guide the treatment of the various factors in the experimental design are given in Section 2.1.2. The experimental design is determined by the characteristics of the test samples covered in Section 2.1.3 and by the procedures used in defining the inspection tasks covered in Section 2.1.4. A discussion of the character and the number of facilities to be visited is given in Section 2.1.5.

2.1.1 Variables Affecting Results

There are many factors related to specific facility characteristics that could impact reliability numbers. The amount of light, the level of noise, the level of comfort, and the procedures and management structures of a facility could all affect the inspection task.

Inspector related factors include: the amount of training in eddy current testing, the recentness of the training, previous experience with lap splice inspection, and the recentness of that experience. Individual inspector traits, such as susceptibility to boredom and interactions with shift work, could also influence results.

The NDI system under study (high-frequency eddy currents) is general enough that a wide range of equipment with a wide range of capabilities is employed in the field. Table 2-1 lists typical eddy current equipment and shows the expected variation in a number of characteristics. The list is only of equipment employing scopes. Eddy current equipment employing meters is also used in inspections.

In addition to the above factors, which are specific to the inspection system, flaw characteristics can also impact reliability. The angle at which a crack emanates from a rivet hole could influence its detectability. The condition of the lap splice rivets and the characteristics of the material around the rivets could influence eddy current readings and thereby impact the detection reliability.

There are multiple lap splice joints on an aircraft. The probability of detecting flaws may depend on the particular lap splice being inspected, because of accessibility and other constraints put on the inspector.

Table 2-1. Characteristics of selected eddy current instrumentation

Feature	Manufacture/Model: Foerster AF	Nortec NDT-19	Zetec MIZ 20A	Rohmann B1-SDM	Hocking Phasec 1.1	Magnaflux 810
Size (HxWxD)	7"x8.85"x13.85"	5.5"x12"x15"	6.5"x10.5"x14.5"	4"x10"x13"	4.1"x10"x12.2"D	5.5"x14"x15"
Weight With/WO Battery	16 lb / 21 lb	19 lb	20 lb	14.5 lb / 15.2 lb	13 lb	26 lb
CRT Size/Screen Display	5"/Digital	5"/Digital	2.25"x4.5"/LCD	4"/Hybrid	2.6"x3.5"	5"/Digital
Battery Charging Time	14 hr	8 hr	8 hr	1 hr fast charger	14 hr	14 hr
Battery Life	8 hr	8 hr	8 hr	8 hr	6 hr	6 hr
Frequency Range	100 Hz - 10 MHz	100 Hz - 3 MHz	50 Hz - 2 MHz	10 Hz - 10 MHz	80 Hz - 10 MHz	40 Hz - 6 MHz
Probe Types	Refl/Bridge Abs/Diff	Refl/Bridge	Refl/Bridge Abs/Diff	Refl/Brdg Abs/Diff/Res	Refl/Brdg Abs/Diff/Res	Refl/Bridge Abs/Diff
Display Memory	None	2	2	4	5	1
User Programs in RAM	100	16 Numeric only	16 Numeric	50, multiples of 50	32	28
Analog Out	Yes	Yes	Yes	Yes	Yes	No
Digital Out	Yes	Yes	Yes	Yes	Yes	Yes
Interface/Printer	RS232,Video	Video Printer	RS232,Serial, Video	RS232,Band, Select.	RS232,Video	Video Printer
Computer Control	Yes	No	Yes	Yes	Yes	Yes
Hardcopy Printout	Serial	Video	Serial,Video	Serial	Serial	Video
Imaging of Cracks	No	No	No	Yes	No	No

2.1.2 Experimental Objectives

The major objective is to assess the reliability of field inspections of lap splices using high-frequency eddy current NDI procedures. The emphasis is on inspections as they occur in the airline maintenance and inspection facilities.

Secondary objectives are established to help understand the factors influencing reliability and also to assess the experimental technique. The factors influencing the inspection results can be categorized into: (1) those that are specific to eddy current lap splice inspections, and (2) those that are more general and would be present in any NDI reliability assessment field experiment. Understanding the first category helps in gaining a better understanding of the lap splice inspections and is necessary if improvements are to be made to the inspection process. Knowledge in the second category transfers to other NDI technologies, thereby reducing the need for a full replication of an extensive, costly field experiment, such as the one given here.

The following objectives have been established for the eddy current lap splice inspection experiment.

1. Assess Effects of Off-angle Cracks. Flaw characteristics besides length are expected to influence detectability. One such characteristic is the angle at which the flaw occurs with respect to the usual or expected direction of crack growth. These off-angle (from horizontal) cracks have been observed and it is important to determine the effect of this factor under field conditions. [4]

2. Assess the Effect of Inspecting Painted Versus Unpainted Surfaces. Procedures do not require that paint be removed when there are two or fewer layers and rivet locations can be observed. Thus, painted and unpainted surfaces represent variations that are likely to exist in field inspections.

3. Characterize the Reference Standards Used Within a Facility. Before any inspection takes place an inspector should calibrate the equipment against a reference standard. Since the reference standard theoretically sets a detection threshold based on the length of flaw contained within it, variation in reference flaws can represent a major source of inspection variation. Characterization of the reference standards provides a quantification of this source of inspection variation.

4. Assess Effects of Accessibility. There are multiple lap splices around a fuselage. Each one can represent different inspection conditions according to how accessible the inspection sites are and according to the physical demands placed on the inspector. It is thus desirable to reflect a range of accessibility in the experiment to gage the potential impact of this factor.

5. Assess Inspection Time Effects. Inspectors are often asked to perform inspections over an extended period of time. It is thought that "boredom" could come into play and that the reliability of the inspections performed initially could differ markedly from those performed well into the task.

6. Gather Facility Specific and Inspector Specific Data as Potential Explanatory Factors. The facility specific and inspector specific factors will not be included in the set of experimentally controlled variables. However, the information on these variables will be gathered and analyzed, as they are believed to affect the reliability of inspections. Light levels will be measured at the time of inspections. Although not prespecified, if information is available about the experience level and the recentness of experience for the pool of potential inspectors, it will be used to obtain a breadth of these factors in the overall experiment.

(Objectives 5 and 6 are not only for the specific task of lap splice inspection, but also will provide information that should be transferable to other NDI assessments. The following three objectives are established to obtain additional information that transfers to other NDI reliability assessments.)

7. Provide Baseline (Laboratory Environment) Inspection Reliability Assessments. A laboratory baseline is essential for providing a fiducial point for determining the total effect of human factors and field conditions on the reliability assessments.

8. Assess Effects Connected with Shift Work. It is likely that many of the facilities visited will have inspection activities spread across several shifts. If shift effects exist, they are likely to apply to other inspection tasks.

9. Assess the Effect of Specimen Definition. Specimens used in field experiments can be designed and fabricated based on various rationales. Controls on flaw sizes, distributions, and orientations can be imposed for statistical design reasons, or flawed specimens can be designed to simulate "naturally" occurring flaws. Any differences in the estimates provided are artifacts of the experimental techniques. Approaches for future reliability studies would be influenced by the knowledge of any differences.

2.1.3 Experimental Design of Test Samples

Two types of test samples will be used in the experiment. One type will be 20 inches. by 20 inches. specimens fabricated to simulate fuselage lap splice joints on the Boeing 737. The other type of test sample will be 10 ft by 6 ft panels, produced with all of the structural components found in an aircraft fuselage. These panels will include two longitudinal lap splice joints and will be curved to match the nominal 75 inches. radius found on the Boeing 737.

In all of the test samples, the lap splice being simulated will have three rows of rivets. Only the top row of rivets will contain flaws and be inspected in compliance with FAA AD 88-22-11.

Two types of test samples are included to address Objective 9. The smaller specimens will have flaws that are controlled in placement and in distribution. The larger panels will be more "natural" in the flaw characteristics. Details of the fabrication are given in Sections 2.2.1 and 2.2.2 and in Appendix B.

Thirty six of the small specimens will be used in this experiment, providing 720 rivet inspection sites. Of these, 559 will be unflawed sites and 161 will be flawed sites. The specimens will be mounted end-to-end on a frame such that they simulate two 30-foot lengths - there will be an upper and lower row of aircraft fuselage lap splice joints. Both the frame and the specimen mounting are described in detail in Test Frame/Support Structure Section 2.2.3 and Appendix B.

Each row represents a different level of accessibility and mode of operation with respect to the interactions between the inspector, the inspection site, and the inspection equipment. The top row can be inspected in a standing position. The bottom row will require the inspector to crouch. Thus, Objective 4 is addressed.

Each of the small specimens will contain fatigue cracks at one of three density levels. The crack density levels for each panel are "none", "low" (1 to 3 holes with cracks), and "high" (7 to 9 holes with cracks). Crack lengths will, for the most part, be in the range of 0.04 inches. to 0.20 inches. Some cracks as small as 0.02 inches. will also be included. One half of the cracks will emanate from the left side of the holes while half will emanate from the right side. The placement will be randomly determined. Thirty two of the rivet locations will contain two cracks of roughly the same magnitude that will emanate from both sides of the rivet hole.

Including rivet sites with cracks from both sides of the hole will enable a test of the hypothesis that the probability of detection associated with the rivet can be derived by treating each of the cracks independently. Questions such as this are important in determining the proper analysis for multiple site damage scenarios when using POD curves. One of the specimens containing nine cracked rivet sites will also contain a 1-in. crack that extends from hole to hole. We expect that all inspectors will find this crack.

In addition to crack density, each small specimen will also possess one of three levels of "off-angleness" for the direction of crack growth. The three levels are: (1) 0° off horizontal (i.e. along hole centerline), (2) 11° off horizontal, and (3) 22° off horizontal. Having three levels provides data for characterizing "non-linearity" in the effect of crack growth direction on detection reliability. (See Section 2.4 Data Analysis). The maximum of 22° for the off-angle cracks is based on reported occurrences at this level. [4]

Table 2-2 gives the intended distribution of cracks, including the crack lengths and direction of growth. Table 2-3 shows the specimen distribution with respect to the number of cracks per specimen and the direction of crack growth. The total number of cracked rivets are also listed in these tables.

Table 2-2. Desired distribution of cracks by length of crack and crack direction

	Crack direction			
Crack Length (in.)	0 °	11°	22 °	Total
.02 to .04	7	2	2	11
.04 to .12	66	20	20	106
.12 to .20	26	8	8	42
1 *	1			1
Totals	100	30	30	160

* One crack will extend from one rivet hole to the next.

The larger panels allow cracks to grow "naturally," with no controls on their orientation or relationship to each other. However, getting meaningful POD estimates will require that cracks be produced in the .04 inches. to .20 inches. range. The objective is to produce two of these large panels and to have 15 to 25 flawed sites per panel in the .04 to .20 inches. range. A total of 108 rivets/panel will be inspected.

<u>Specimen Finish</u> - The Boeing procedures for inspecting lap splice joints call for the stripping of paint if there are more than two layers or if rivet heads cannot be visually located. However, a particular facility may strip the paint as a matter of procedure. The small specimens will be painted or unpainted according to the facility's normal mode of operation. One of the large panels will be painted and one unpainted throughout the experiment.

Table 2-3. Panel distribution by desired number of cracked sites and crack direction. Also shown is the total number of cracked rivets ( ).

Number of Cracked sites /Panel		Crack direction 0°	11°	22°	Totals
low density	1	3 (3)	1 (1)	1 (1)	5 (5)
	2	4 (8)	1 (2)	1 (2)	6 (12)
	3	3 (9)	1 (3)	1 (3)	5 (15)
high density	7*	3 (21)	1 (7)	1 (7)	5 (35)
	8*	4 (32)	1 (8)	1 (8)	6 (48)
	9*	3 (28)	1 (9)	1 (9)	5 (46)
	Totals	20 (101)	6 (30)	6 (30)	32 (161)
	Uncracked panels				4

* Some rivets in each panel will contain cracks from both sides of the hole (see Figure 2-1). One of the 9-crack panels will have a 1 inches. crack extending to an adjacent rivet. Thus, one additional rivet is included in the 9-crack panels.

A practical consideration related to the specimen finish is the amount of surface damage that results when the probe contacts the surface being inspected. The unpainted surfaces will become scratched and paint will be removed from the painted surfaces, which may be a problem in areas where the inspectors spend more time because of flaw indications. This is unacceptable since the circular mars on the surface will provide unrealistic visual clues to subsequent inspectors.

Two methods to eliminate these visual clues are considered. One is to cover the row of rivets with a thin, transparent tape that would act as a surface protector. The tape would also allow the inspector to mark the test specimens and would provide a semi-permanent record of each inspection to help eliminate data recording errors. A second alternative is to repaint or rebuff the panels whenever the surface damage is excessive.

A small-scale experiment consisting of rotating different types of probe tips on differently protected surfaces was performed on an aluminum aircraft wing section. The variables investigated were: (1) type of probe tip - plastic, aluminum, steel, and "sharp" (a .025 inches. mechanical pencil tip); (2) surface - bare aluminum, painted aluminum, bare aluminum buffed after test, painted aluminum protected with three types of Scotch transparent tape, (3) probe tip revolutions - 20 or 200 revolutions corresponding to approximately 5 and 50 inspections.

The results of the experiment show that the bare aluminum is easily marked with everything but the plastic probe material. It is possible to buff out the 20 revolution marks using a commercial grade "finishing pad." Indications are that this would be necessary after every one or two inspections to eliminate the added visual clues. Over the life of the experiment, it is estimated that rebuffing a bare aluminum surface would remove from .005 inches. to .010 inches. of the surface. This could have a major affect on the repeatability of the test samples from the beginning to the end of the experiment. Also, if painting were involved, the paint drying time would be added to the time taken for refurbishing. The loss of repeatability and the added man power, time, and costs are enough to warrant using a protective tape.

There are trade-offs in using or not using the protective tape. The issue has been addressed with expert input as to the effect on the inspection task. Weighing all factors we have decided to employ the use of tape.

The use of protective tape presents the same surface condition to all inspections regardless of original surface finish. The experimental protocols will call for a monitor to cover the reference standard surfaces with the same protective tape that is used on the test samples. The inspector will then follow usual calibration procedures; therefore, variations resulting from the treatment of the reference standard with regards to painted and unpainted surfaces will still be present. The inspector will also have the same visual presentation to which he is accustomed; therefore, Objective 2 (page 6) is addressed to the extent indicated.

2.1.4 Inspection Procedures

At each facility, there will be four basic layouts or arrangements of the small specimens. The basic layout has the inspector going from an initial inspection period with no cracks (about 8 minutes), to a period of inspecting at a relatively low flaw density (10%), followed by a period of high flaw density (40%). This sequence is repeated with the inspection of the other lap splice row.

The initial period with no cracks is maintained in all the layouts. The intention is to counter the natural tendency of the inspector to believe that the experimental apparatus contains many flaws. The three additional layouts are derived by reversing the order of inspection on the basic layout and by interchanging the rows of panels (see Table 2-4). With the four layouts, each crack will appear in both top and bottom lap splice rows and will appear in each of four time periods of inspection in a balanced manner. This will ensure the ability to cleanly estimate accessibility, time, and flaw density effects (Objectives 4 and 5, page 6).

The inspectors will mark the rivet locations where a flaw is detected directly on the tape covering the specimen. If the sliding probe method is used as an initial screen, all indicated flaw locations will be noted in the data base. For the subsequent oversize template method, the inspector will be asked to give a three-level confidence rating to all flaw indications. The different ratings will be used as criteria changes for the purpose of determining ROC curves.

Table 2-4. Layout of panels. Lc,Hc - low and high density cracks on centerline
Le,He - low and high density cracks at 11°. Lt,Ht - low and high density cracks at 22°.
PP,UP - painted and unpainted large curved panels.
Each line of a layout corresponds to a different row of panels.

lay out	Panel Position 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18		
1	0	0	Lc	Le	Lc	Lt	Lc	Lc	Le	Lc	Hc	Ht	Hc	He	Hc	Ht	Hc	Hc	PP	UP
	0	0	Lc	Lc	Lt	Lc	Le	Lc	Lt	Lc	Hc	He	Hc	Hc	Ht	Hc	He	Hc		
2	0	0	Lc	Lc	Lt	Lc	Le	Lc	Lt	Lc	Hc	He	Hc	Hc	Ht	Hc	He	Hc	UP	PP
	0	0	Lc	Le	Lc	Lt	Lc	Lc	Le	Lc	Hc	Ht	Hc	He	Hc	Ht	Hc	Hc		
3	0	0	Hc	Hc	Ht	Hc	He	Hc	Ht	Hc	Lc	Le	Lc	Lc	Lt	Lc	Le	Lc	PP	UP
	0	0	Hc	He	Hc	Ht	Hc	Hc	He	Hc	Lc	Lt	Lc	Le	Lc	Lt	Lc	Lc		
4	0	0	Hc	He	Hc	Ht	Hc	Hc	He	Hc	Lc	Lt	Lc	Le	Lc	Lt	Lc	Lc	UP	PP
	0	0	Hc	Hc	Ht	Hc	He	Hc	Ht	Hc	Lc	Le	Lc	Lc	Lt	Lc	Le	Lc		

Inspection layouts by panel numbers

lay-out	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
2	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
3	2	1	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3
	20	19	36	35	34	33	32	31	30	29	28	27	26	25	24	23	22	21
4	20	19	36	35	34	33	32	31	30	29	28	27	26	25	24	23	22	21
	2	1	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3

2.1.5 Number of Facilities and Inspections

Each of the four layouts will be inspected by a different inspector. The inspectors will be chosen to represent every shift that the facility operates to address Objective 8. For those facilities with three shifts, the fourth inspector will be chosen to balance the representation on all three shifts across facilities. At all facilities, the initial inspector will be asked to do two inspections. The second inspection will be at the end of the facility visit. The result will be a total of five inspections at each facility.

Table 2-5 shows the U.S.-based airlines that fly Boeing 737s in their fleets as of January 1992. In addition to the airlines, 32 independent repair stations capable of performing heavy airframe maintenance are identified in Table 2-6.[5]

Table 2-5. United States Airlines Operating Boeing 737 Aircraft

Airline	Fleet Size
Alaska Airlines	7
Aloha Airlines	19
America West Airlines	65
American Airlines	5
Carnival Airlines	4
Continental Airlines	94
Delta Airlines	72
Markair	12
Midway Airlines	1
Sierra Pacific Airlines	7
Southwest Airlines	123
Spirit of America Airlines	1
United Airlines	195
USAir	229
TOTAL	**834**

Source: Federal Express Aviation Services, Inc. Commercial Jet Fleets, Vol. 1, Jan. 1992

It is not uncommon for the major airlines to have more than one maintenance facility. Thus, it is estimated that there are from 30 to 40 total facilities where Boeing 737 lap splice inspections could be performed. To have a reasonable chance (90%) of including at least one out of the most extreme 10% of the population in a random sample, 16 to 17 facilities should be selected.[1] Rather than relying on a totally random sample to reflect the expected facility variation, classes of facilities can be targeted to try and cover the suspected major variation, which is the tack recommended here.

There are many factors that could be used to characterize inspection facilities with respect to a specific inspection task. Some examples of the factors are number of times the task is performed, proportion of total work represented by the task, independent or airline owned, inspector training programs, union or non-union shop, management procedures, and hangar conditions (size, lighting, noise, etc.). Some of the many factors can be associated with facilities prior to inclusion in the sample; others will not be known prior to visitation and may not ever be explicitly known. To adequately cover the range of possibilities for the various variables, we recommend that 12 facilities be visited. These 12 facilities will represent a judgement sample based upon representing the range of facility characteristics that can be known in advance.

Table 2-6. Independent Maintenance and Repair Stations

Repair Station	Location
AAR Oklahoma	Oklahoma City, Ok.
Aerotest, Inc.	Mojave, Ca.
Aircraft Maintenance Services, Inc.	Miami, Fla.
Airtech Service	Miami, Fla.
Associated Air Center	Dallas, Tx.
Boeing Wichita Company	Wichita, Kan.
Butler Aviation	Newark, NJ
Chrysler Technologies Airborne Sys.	Waco, Tx.
Commodore Aviation Services	Miami, Fla.
Cross Continent Aircraft Services	Smyrna, Tn.
Dalfort Aviation Services	Dallas, Tx.
Dee Howard Company	San Antonio, Tx.
DynAir Tech of Arizona	Phoenix, Az.
DynAir Tech of Florida	Miami, Fla.
E-Systems, Inc.	Greenville, Tx.
Elsinore Airframe Services, Inc.	Waco, Tx.
Evergreen Air Center	Marana, Az.
Florida West Airlines	Miami, Fla.
Greenwich Air Services	Miami, Fla.
Hughes Aviation Services	Las Vegas, Nev.
Intertec Aviation	Goodyear, Az.
Lockheed Aeromod Center	Greenville, SC
Lockheed Aeromod Center	Tucson, Az.
Midway Aircraft Engineering, Inc.	Miami, Fla.
NARCAM Aircraft, Inc.	Hialeah, Fla.
Page Aviation, Inc.	Orlando, Fla.
Pemco Aeroplex	Birmingham, Alabama
Pemco Aeroplex-Clearwater	Clearwater, Fla.
Pemco Aeroplex-Dothan	Dothan, Ala.
Timco	Greensboro, NC
Tracor Aviation	Santa Barbara, Ca.
Tramco	Everett, Wa.

2.1.7 Reference Standard Data

Objective 3 is to characterize the reference standards used to set up the eddy current equipment within the facilities. The NDI specialist who will be traveling with the experiment will characterize all reference standards used for setting up equipment used in lap splice inspections. The characterization will be against a master reference that will travel with the experiment. The data recorded will be variables data and will directly reflect the variation induced into the inspection process by using different reference standards.

2.1.7 Laboratory Baseline

Objective 7 was to provide a baseline for determining the total effect of the human factors and field conditions on the reliability assessments. This will be done by having four inspections of the experimental specimens by four different inspectors prior to the facility visits. The inspections will be done in a laboratory setting with no time pressures on the inspectors. One of the inspectors will be asked to do two inspections, with the inspections separated in time by several days. In terms of analysis, the laboratory baseline becomes another "facility". The aggregate laboratory data can then be compared directly against the data from each of the facilities.

2.2 Design and Manufacture of Experimental Specimens

Two types of test samples will be employed in this experiment. One type is test panels that will be able to be moved and presented according to the layouts presented in Table 2-4. The other type is panels that incorporate fuselage structure into the sample before fatigue cracks are grown. Each is explained more fully below.

2.2.1. Lap Splice Joint Test Specimens

The test panels used in this experiment will simulate fuselage lap splice joints found on the Boeing 737 aircraft. They consist of two plates fastened together, using three rows of rivets, with a 3 inch overlap. The upper plate will contain the cracked holes in the critical first row of rivets. This panel specimen is shown in Figure 2-1.

Panel Geometry. The completed panel will measure 20 inches by 20 inches. These dimensions were arrived at after careful consideration was given to both the aircraft structure being modeled and the maximum plate size that could be economically produced without sacrificing the ability to generate the desired flaw distribution. The 20 inch width allows the panels to be mounted on a typical aircraft circumferential rib spacing of 20 inches. The 20 inch width also simulates the aircraft fuselage in the local area where the inspection task takes place. When panels of this size are assembled on a test stand, they will provide a good representation of the longitudinal lap splice joint. The method used to produce the flaws in the upper plate, along with the requirement for off-angle cracks, are the limiting factors in the final height of the panel. These issues are described in Appendix B.

Specimen Manufacture. The test panel production is made up of two distinct tasks. One task is the crack initiation and growth and the other task is riveting the plates together to produce the final test specimen. The most difficult aspect of constructing these panels is the production of the upper cracked plates where the crack distribution is very specific in number, length and orientation. Numerous companies (Control Tech, Metcut Industries, Teledyne Engineering, Foster-Miller Corp., Martin Marietta, Cortest, SNL, AEA) with expertise in this area were contacted in order to obtain information regarding the preferred method of fabrication and also to obtain time and cost estimates. Each company that felt capable of producing these plates determined that a tension-tension loading was the best way to generate cracks in the upper plate of the lap splice joint. More detail is given in Appendix B.

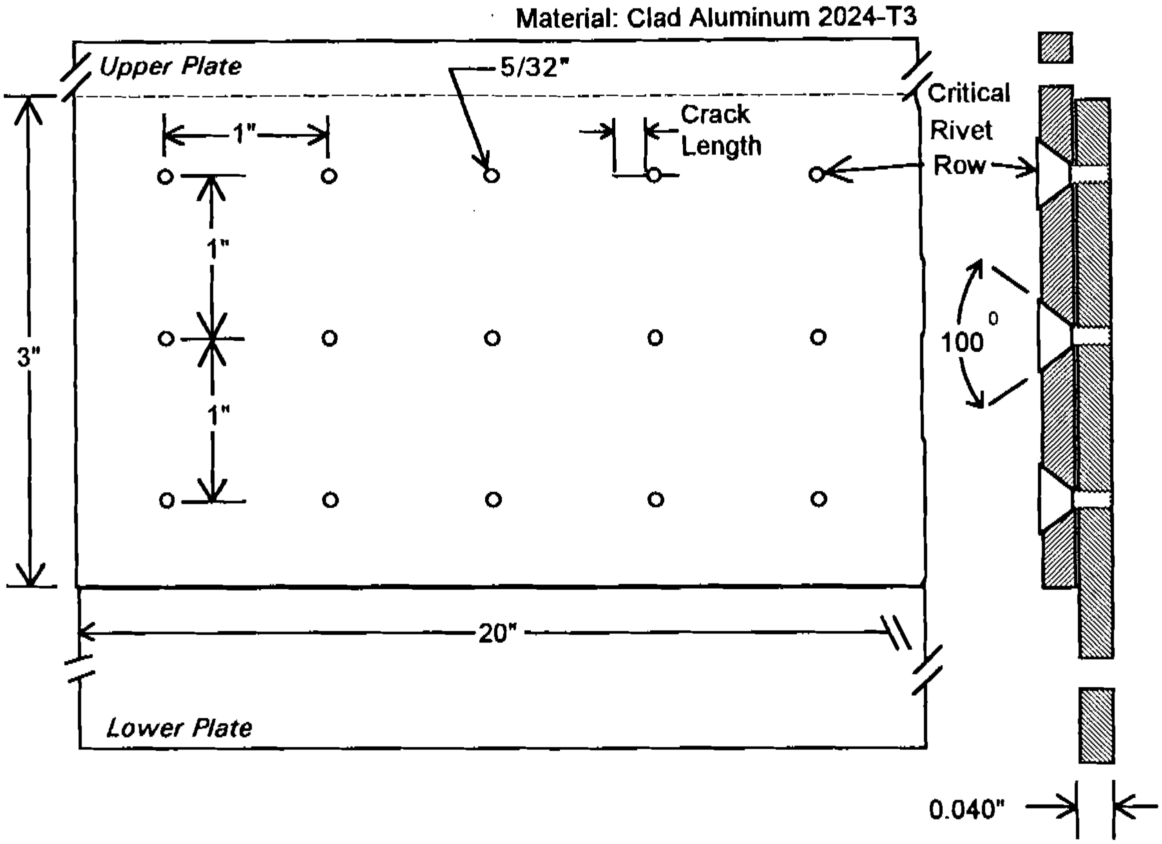


Figure 2-1. Test specimen configuration

2.2.2. Full-size Aircraft Panels

To provide test specimens with more "natural" crack distributions; that is, panels that have not used starter notches or controlled loading to achieve a designed crack distribution, the POD Experiment will also include two full-size aircraft panels. With these panels it will be possible to: (1) provide more realism both in the size of the panels and the presence of "real" crack distributions and (2) test whether differences exist in the estimates of POD curves when using smaller specimens with more controlled crack distributions versus larger panels that contain natural crack distributions.

Aircraft Test Panel Overview. These full-size panels will be produced with all of the structural components found on an aircraft fuselage, will include one longitudinal lap splice joint, and will be curved to match the 75 inch radius found on the Boeing 737 aircraft. The panels will be fabricated by Foster-Miller, Inc., and will be similar to the panels which Foster-Miller has produced for other FAA investigations. (see Figure 2-2). Cracks will be generated in the panels using a custom designed load machine that Foster-Miller developed for this purpose. The structural test frame provides a bi-axial load (hoop stress and axial stress) that simulates the fuselage loads incurred during aircraft pressurization. The loads are applied in a cyclic manner and cracks are allowed to initiate as they would in high cycle aircraft. A complete description of the Foster-Miller panels, the load facility, and the initial test program carried out in this facility is provided in Ref. [6]. A summary follows.

Full-Size Test Panel Design and Fabrication. The test panel is designed to be more realistic than the small specimens both in size and features, which include the following:

1. Fuselage construction like the Boeing 737.

2. Thin-skinned (0.040 inch thick) shell using clad 2024-T3 aluminum alloy.
3. Stiffening in the circumferential direction by ribs and longitudinally by stringers.
4. Stringers and frames fabricated from 7075-T6 aluminum alloy sheet.
5. Rivet construction that adheres to Boeing aircraft specifications.
6. Skin panels joined by a lap joint using three rows of countersunk rivets.

2.2.3. *Test Frame/Support Structure*

The support frame must adequately model the geometry of the chosen inspection area. The frame should also contain all of the features that are necessary to assure inspector "buy-in." The specimen support frame for the experiment is designed to hold the small test specimens as well as the full-scale aircraft panels. It was also designed for ease of assembly, ease of shipping, and for repetitive alignment of the test specimens. These features are especially important since this experiment requires the frame to be assembled and disassembled several times. When the support frame is completely assembled with the test specimens it will model a total of 50 ft length of an aircraft fuselage. Thirty feet of this "fuselage" will consist of the 20 inch wide test specimens mounted end-to-end on the frame. The remaining 20 ft will be comprised of the two 10 ft, full-scale, Foster-Miller panels.

The support frame is designed for use beyond this experiment and will be used in the FAA/AANC Validation Center following the completion of the experiment.

Further details of frame design are given in Appendix B.

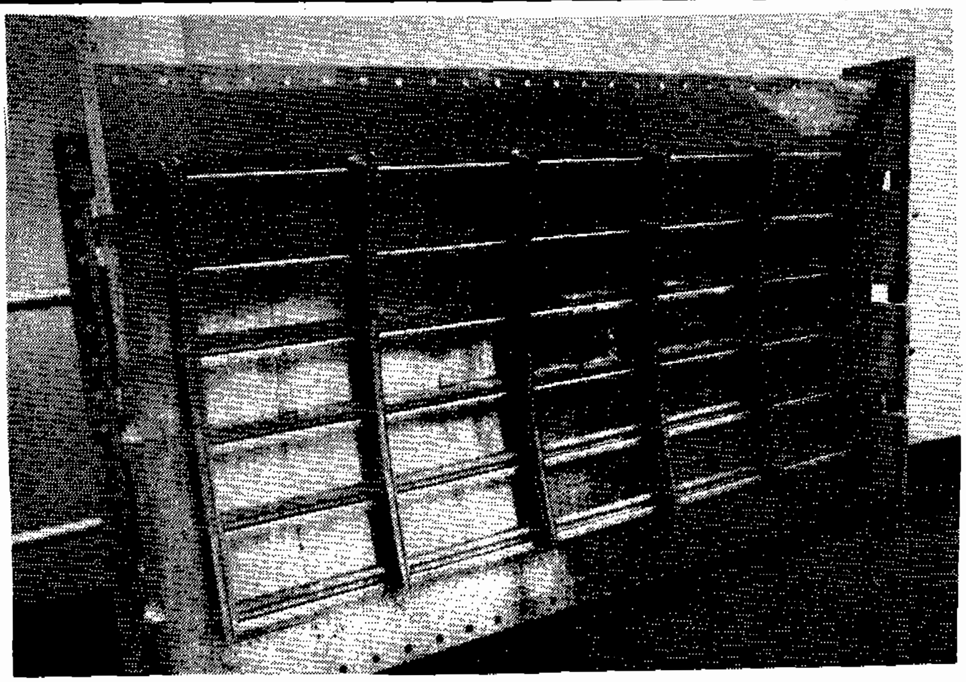
2.3 Characterization of Lap Splice Specimens

The purpose of specimen characterization is to confirm the size of the cracks and subsequently enter the information into a data base. The characterizations will be done following the manufacture of the specimens.

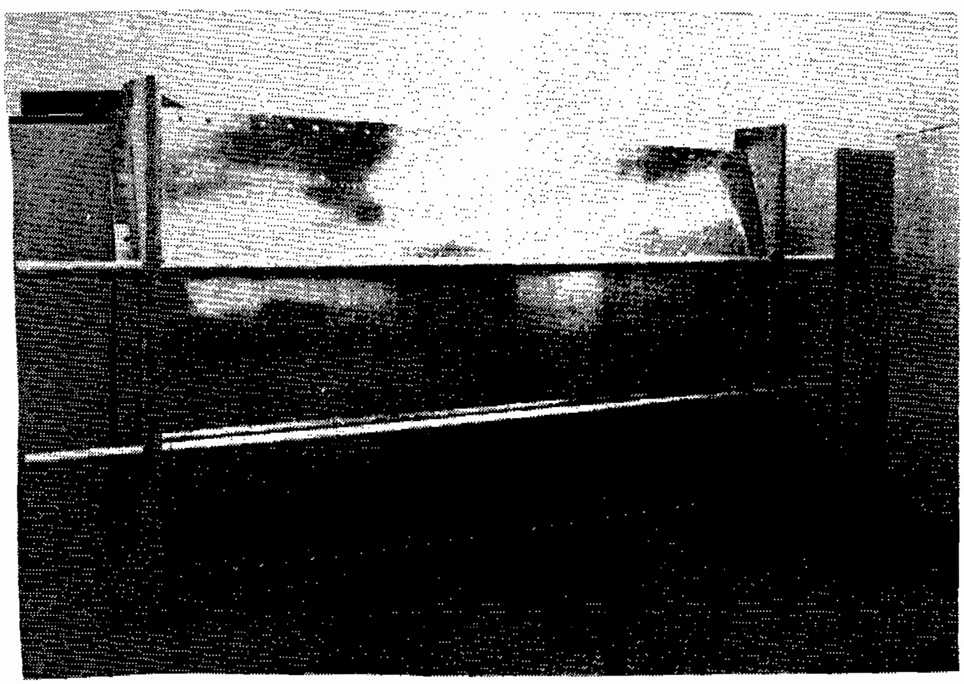
Candidate techniques that may be used include laser profiling and liquid penetrants. Laser profiling allows the use of automation and the obtaining of images that can be processed and displayed. Laser profiling can be done using Rodenstock Precision Optics, and the results will be in the form of scan disks from which the data can be extracted and color images made. Liquid penetrants are standard in detecting and measuring surface cracks. Liquid penetrant testing is likely to be done using FP-99A water washable fluorescent penetrant and D-701 developer, manufactured by Met-L-Chek. These materials exhibit minimum sulphur and halogen content per OSHA requirements. They also do not require special disposal considerations. The FP-99a has a level 3++ sensitivity rating providing good capability for sizing the cracks contained in the panels. The test results would be photographs of each plate while it is under the black light.

Eddy current imaging, plastic replication, and ultrasound techniques are other methods of measurement for consideration to increase the confidence in the results.

Capability for recharacterizing the samples will be maintained throughout the experiment.



(a)



(b)

Figure 2-2. Full-scale test panel: (a) interior, (b) in handling fixture.

2.4 Data Analysis

The data will be analyzed for POD through the log odds model. [1] The parameters (α and β) in that model can be expanded to reflect a dependence on various explanatory factors. The basic model equation that reflects the controlled factors of the experiment on the small test specimens is given by

$$\ln[POD(a)/(1-POD(a))] = F + S + A + D + T + V + \beta \cdot \ln(a),$$

where a is the crack length, F reflects a facility average, S reflects the shift (three levels), A is the factor for accessibility (two levels), D is the factor for the density of flaws (two levels), T is the factor for the time into the task (four levels), and V reflects different flaw angles (three levels). The experimental design allows for not only the estimates of each of the main effects given above, but also allows for estimating most of the interaction effects.

Although not reflected in the above model, interaction effects between the given factors and β will also be analyzed.

The basic model equation for the large panels is given by

$$\ln[POD(a)/(1-POD(a))] = F + S + P + \beta \cdot \ln(a),$$

where F and S are facility and shift, respectively, and P is the painted/unpainted factor. (Note: the painted/unpainted factor was not included in the model for the small specimens because of the uncertainty about the balance between the facilities performing inspections on painted versus unpainted surfaces.)

A comparison of the composite α's and β's from each of the test types will be analyzed for indications of differences because of the type of specimen being inspected.

The ROC curve that incorporates false calls into the analysis will be determined from the three confidence levels that the inspectors are to provide with each positive flaw response. Empirical ROC curves can be determined for each inspection and condition within each inspection (such as crack angles). Summary measures can then be determined from these individual ROC curves (see Ref. [1]). For example, one accepted index for summarizing ROC curves is the area under the curve, denoted "A." This index is an average probability of detection, where the average is taken over the criteria range. The criteria range corresponds to changing the threshold for calling a signal a flaw. The index "A" will be modeled in the same manner as was the log odds for the POD curves.

The index "A" will also be determined for each of several groups of similar crack lengths. This enables an assessment with respect to signal strength (crack length).

The models discussed above do not contain variables related to uncontrolled factors. Observations of many of these variables will take place at the time the inspections occur and their values will become part of the data base. Exploratory Analysis of Variance (ANOVA) and regression models will be pursued with respect to these factors in both the POD and the ROC curves. The extension of ANOVA into Multivariate Analysis of Variance (MANOVA) occurs when more than one response variable is analyzed at a time; for example, simultaneously analyzing α and β in the log odds model. Similarly, if two or more responses are modeled with the same set of explanatory factors in a regression setting, the techniques of multivariate regression analysis can be used. These techniques will be used for analyzing the data.

2.5 Protocols

The protocols are designed to run the whole experiment consistently covering interactions with the facilities, actions of the participants and data analysis. A flowchart of activities taking place at each facility is given in Figure 2-3.

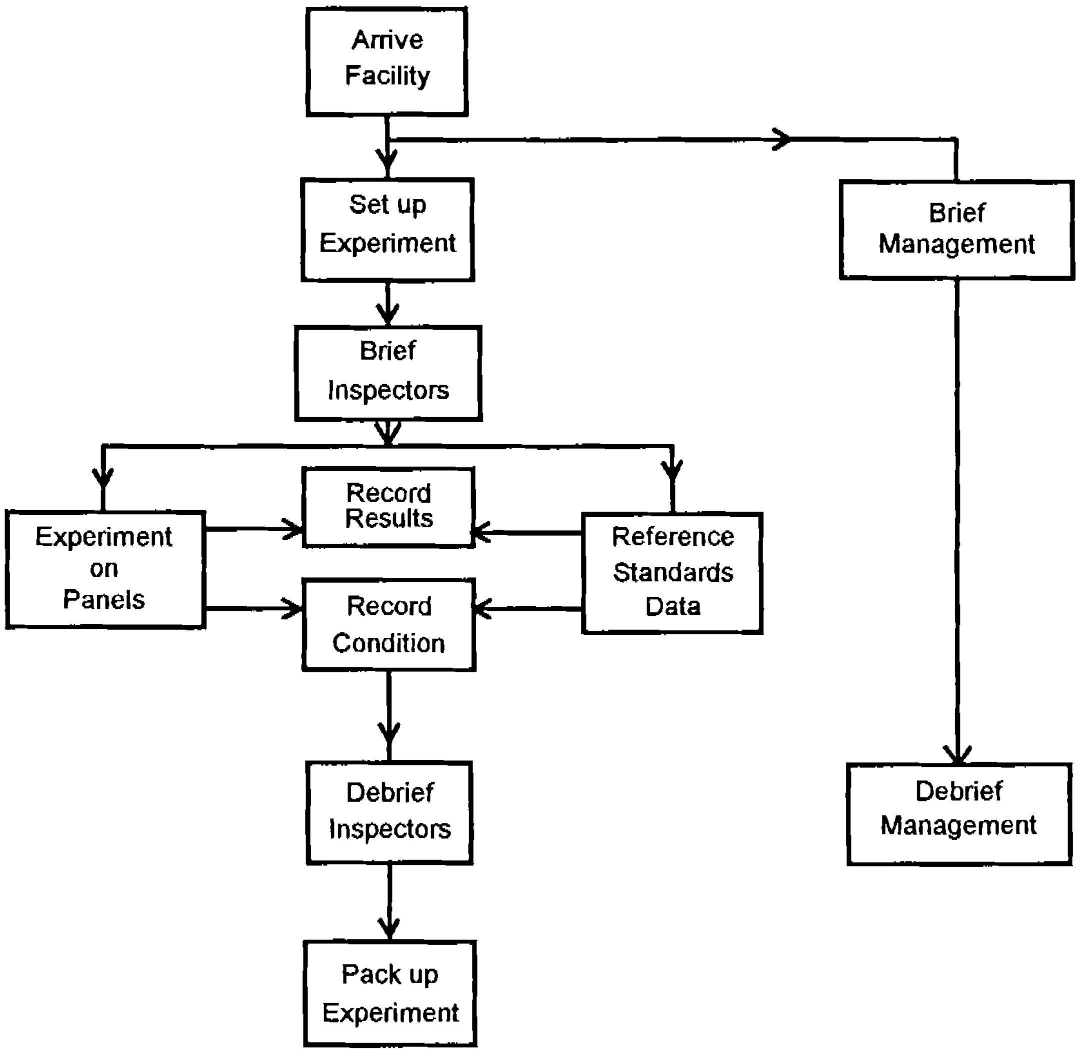


Figure 2-3. Experiment Procedure.

The personnel responsible for the on-site implementation of the experiment are termed monitors. Their protocols define what actions the monitors will take during the experiment, including briefings to the facility management and inspectors.

Similarly, a basic set of protocols for the inspector is required to define the procedures he will use to carry out the experiment and the modifications necessary to run the experiment.

These protocols will be drafted prior to a dress rehearsal to enable realistic trial runs to be made. The final protocols will include the lessons learned and suggestions obtained from the dress rehearsal participants and observers.

Pre- and Post- Experiment Protocols

A background information questionnaire will be sent or taken to all participating facilities to provide an overview of the facility operation. This is tied to the logistics to aid scheduling of the experiment. The questionnaire will include information on the size of facility, number of inspectors, range of aircraft inspected, and experience with Boeing 737s. This information will be coded to maintain facility confidentiality.

Procedures for storing all information and its coding at the end of the experiment will be developed.

Monitor Protocols (Handbook)

The protocols for the monitors will form their Handbook for the experiment, including guidance on the structure and purpose of the lap splice experiment and guidance on specific human-related issues that might arise, such as:

- What information may be disclosed to inspectors (including the objectives of the research and the ways the inspector's performance will be recorded).
- If and how monitors should interfere with an inspection trial in progress.
- Details of maintaining confidentiality in records.
- How the monitor should act with other personnel and management at the participating facility.
- How to conduct the reference standards experiment.
- What logbooks, records and data bases will be maintained.

These protocols are defined in more detail in Appendix A along with samples of data gathering forms.

Inspectors Protocols

These protocols will define the procedures and data collection which relate directly to the inspector. They will address the following:

- information to be given to the inspector prior to his participation in the experiment,
- the pre-experiment briefing document to be signed by the inspectors to indicate their agreement to participate,
- certain confidentiality procedures specifically related to the inspector,
- inspection procedures and equipment to be used,

- pre- and post-inspection questionnaires.

In this case, the Boeing 737 eddy current inspection procedure used at the facility will--whenever possible--be used by the inspector. Though the inspector will use the equipment he would normally choose to carry out this inspection, the monitor will check the equipment to ensure it poses no problems with the experimental set-up.

The protocols also include the information to be obtained on the inspector with respect to training, experience with eddy currents, experience of Boeing 737 lap splice inspection, and how often these tasks are normally carried out.

2.6 Logistics

Logistical planning is the first stage of implementation of an experiment as discussed in Section 2.8 of Ref. [1].

The logistical plan for the POD experiment requires several steps. These steps can occur in both parallel and serial order. Each of the steps is discussed below.

2.6.1 Assembly of Hardware and Dress Rehearsal

Procedures must be developed and tested before the experiment begins. Procedures for hardware assembly will be completed after hardware fabrication, and will be practiced several times before taking the hardware out to a facility. This practice will occur during a "dress rehearsal."

The assembly will be set up with the Foster Miller panels facing one direction and the small specimens facing the opposite direction. This arrangement will provide both a physical and a cognitive (mental) break between inspections of the two types of displays. Although there should not be a long enough break for the inspector to change their mental "set" about how they are inspecting, there should be enough of a break to avoid "jarring" the inspector's willingness to treat the simulation as if it were an actual aircraft.

The dress rehearsal will embody the full procedures of putting the hardware together, changing the order of the small specimens and data collection. The dress rehearsal activities will be held at a third party maintenance facility at the Albuquerque International Airport. We expect that the dress rehearsals will be observed by FAA personnel, AANC personnel, and advisory persons. The observers will be asked to evaluate both the system and procedures for the research and to provide suggestions for resolving problems.

The first portion of the dress rehearsal will consist of practice sessions in erecting and taking down the test specimen hardware, from crated-on-the-truck and back to that same condition. This portion of the dress rehearsal will test both hardware design and the procedures for erecting, making ready, and removing the hardware. We expect that adjustments will be required for the procedures, and perhaps the hardware. Minor adjustments will be made before the data collection portion of the dress rehearsal takes place.

The data collection portion of the dress rehearsal will use eddy current technicians from a third party maintenance facility and/or eddy current technicians from SNL or SAIC. This portion must occur in several stages. In the first stage, the inspectors will be given the standard briefing, followed by a discussion about whether or not the briefing materials are easy to understand and accept. The next stage will be a tryout of the data collection procedures under fully interactive conditions. That is, both the monitors and the inspectors will be allowed to stop the procedure to ask questions, make observations, and suggest changes. After general agreement concerning the system and procedures, from hardware set-up through data collection and takedown of the hardware, the procedures will be followed exactly. Necessary changes, at this point, will be noted and logged, but not made. This stage will be repeated as many times as necessary to ensure that the procedures will yield a smooth-running, repeatable experiment. This stage will be followed by a general meeting of the observers, monitors and inspectors for final discussion of procedures. Thus, the dress rehearsal could require from as little as five to as much as ten days.

2.6.2 Scheduling

There will be more facilities scheduled than will be actually visited. Some of the facilities will be chosen as backup to others. Careful selection will allow minimum disruption because of unavailability of a facility at the scheduled time.

The scheduling program will allow the monitors one week back in their offices every second or third week. Since the monitors will often observe two or even three shifts to obtain the four inspectors needed, they will be working 12- to 16- hour days. Thus, they will need rest and recuperation time frequently or their fatigue will reduce the accuracy of their observations and increase the probability of uncorrected errors in setting up the hardware. The time between trips will be used profitably in catching up on paperwork and assisting with data analysis. The early data analysis will allow recognition of changes in the test specimens early enough to avoid wasted effort in collecting unusable data because of changes.

2.6.3 Storage and Shipment of Test Samples

The manager of the experiment will control and will be responsible for the storage and shipment of the test samples from the time of final characterization. They will arrange for secure storage facilities that will be unchanged for the duration of the experiment. The test samples will be logged into and out of those facilities, and access to them will be limited to avoid mishap. A custodian who has primary responsibility for the test samples will be designated.

The test samples will be shipped from facility to facility using air freight whenever possible. When there are breaks between facility visits (of more than two or three days), arrangements will be made for safe storage, with shipment back to central storage, if necessary. Shipping arrangements will be the responsibility of the custodian at the storage facility, although the monitors will be responsible for oversight of pick up and delivery on facility-to-facility shipments.

2.6.4 Field Adjustments to Loss or Alteration of Samples

A limited number of test specimens (at least 7) will be manufactured with the experimental group of 36 specimens and be maintained as backups. These backups will be kept at the major storage location and arrangements made for air shipment upon demand.

If there is an extreme change in the expected pattern of inspector responses for a given specimen, then a change in crack characteristics may have occurred. If a change in the specimen is suspected, it will be sent back for characterization and a new one put in its place. The new one will not have exactly the characteristics of the old, so the changed pattern must be logged and noted in the data files.

In the case of loss or destruction of test specimens, the adjustment will depend on the percentage of the total specimen group. Any losses less than 50% can possibly be adjusted by increasing inspections of the remaining specimens. Some information will be lost with this procedure; however, adjustments in analysis can be made to salvage as much information as possible. A reduced data set is preferable to terminating the whole experiment.

2.6.5 Post-Experiment Archiving of Test Specimens

When the experiment is completed, the test samples will be characterized to determine if any alterations in the size and distributions took place. (Since the test specimens are never under tension, no changes are anticipated.) This characterization will be logged on the test specimen inventory records. After that, the specimens will be stored in their shipping containers to form a permanent library of well-characterized specimens at the AANC Validation Center.

3. Implementation

This section describes the implementation efforts required to execute the lap splice reliability assessment experiment. In Ref.[1], three major elements were identified: (1) Preparation, (2) Experiment Execution, and (3) Data Qualification. The key elements associated with each of these activities were also identified. In this detailed plan, that structure is further expanded to specifically delineate the activities that must be performed to execute the experiment. This expanded structure is summarized in Table 3-1. Each of the major elements is discussed separately in the sections that follow.

3.1 Preparation

There are, as noted in Table 3-1, nine key elements associated with preparing these experiments. The Activities, as summarized in Table 3-1, are discussed below.

Monitor Assignment

Since this experiment is designed to develop a POD curve and to assure that the human factors contributing to that curve are well understood, we propose that the monitors will be a human factors expert and an NDI specialist. (The performance of the actual inspection activities will be done by maintenance center personnel in each of the centers.) This effort consists of selecting the monitors, identifying alternates, and pursuing the process of training and familiarization necessary to ensure high-quality, efficient operations at the various test sites.

Site Coordination

This type of experiment requires that the numbers and locations of sites be preselected, the timing of the implementation of this experiment be coordinated with site operations, and that alternates be available, if for any reason a primary site is not available. These three elements are the major activities to be performed under site coordination. The coordination process step itself is an iterative one; from the initiation of contact with the upper management at the potentially usable sites, through the process of ensuring near term coordination just prior to the arrival of the equipment and personnel at the test site. This activity is vital to ensuring a smooth, efficient, and unbiased experiment sequence.

Safety

Safety is always a significant consideration in all test efforts. The activities shown in Table 3-1 address the review of OSHA requirements to ensure that all basic safety rules are met in the implementation of the experiment. To this end, a preliminary hazards analysis that will identify potentially hazardous activities will be performed. The hazard mitigation approaches that are be taken will be identified to assure the safety of these operations. Each site will have, in compliance with good working conditions, a safety program of its own. It is most important that when implementing this experiment, these site unique safety considerations be examined so that all of the activities performed by the experiment team comply with site safety rules. The dress rehearsal will help define areas where safety issues are likely to arise.

Sample Acquisition

In preparing for the experiment, sample acquisition goes beyond receipt of the panels and the specimens. A receiving inspection will be performed to ensure that the panels have been prepared in accordance with the drawings and specifications. Each panel needs a carefully marked, unique identification to ensure proper set-up at each site. The generic experiment plan addresses the need for and the process of providing pre-experiment characterization of the panels, cracks, etc. This is, of course, a vital part of preparing for the experiments.

Test Equipment Acquisition

All the equipment (meters, tools, gages, etc.) required for the set-up, tear down, and check out of the experiment at each site will be received, checked out, and calibrated, if necessary.

Shipping and Handling

Since the test is being performed at multiple sites, shipping and handling is an important part of the preparation activities. Containers will be fabricated. Upon receipt of the containers, they will be inspected for compliance with drawings and specifications. Transportation arranged for the samples and the handling equipment will be finalized during the preparation phase. Handling equipment, as it is received, will be inspected for compliance with drawings and specifications. Further, the assembly and tear down of handling equipment, using the tools and the procedures that will be provided at the site, will be checked out as a part of the shipping and handling activities.

Experiment Integration

To ensure a smooth and efficient set of operations at each site, experiment integration is a major preparation effort. Each piece of the experiment, that in some sense must be made compatible with other pieces, will be checked out during these efforts. As noted in Table 3-1, integration of specimens and containers, specimens and mounting fixtures, will be performed to ensure that all of the hardware elements fit together properly. Additionally, as with any new procedure, trial runs of protocols and use of the documentation (i.e., detailed test plan) will be performed to ensure that all significant activities are properly structured in the documentation, and further to ensure that all equipment is functioning as anticipated in the implementation of the protocols. A baseline set of data on the specimens is a vital ingredient to the overall evaluation process. These carefully taken baseline data will be acquired as a part of the experiment integration efforts.

Dress Rehearsal

The dress rehearsal will, to the maximum extent possible, replicate the "real life" experiment as it will be performed at each of the sites. The monitors (human factors expert and NDI technologist) will go through the entire protocol with the dress rehearsal inspectors as if this were an on-site activity. In addition, observers will be invited to critique the process. To ensure that the observers are aware of the overall structure, objectives, basic approach, etc., relevant to these experiments, a briefing for the observers will be prepared and presented. Finally, at the conclusion of the dress rehearsal, the observers will provide their constructive comments and observations through a debriefing to the experiment team.

Storage

We anticipate that there will be times when the specimens and the handling equipment will have to be stored between use at test sites. This element of the preparation phase addresses storage areas, storage containers, storage conditions, etc., so that a smooth transition from the completion of an experiment at a particular site into the storage area and, subsequently out of the storage area to the next test site can be effected as necessary. Additionally, storage of all data will be addressed in this phase of the preparation activities. A central storage area, as well as a uniform process for inputting the data to the central data base, will be set up and checked out as a part of this effort.

3.2 Experiment Execution

Table 3-1 lists five key elements under experiment execution. The structure set up in Table 3-1 for the key elements lays out the sequence of activities and events that constitute the performance of the experiment itself. Each of the five elements is discussed below.

Site Introduction

To ensure that all parties who are a part of the experiment efforts are aware of the objectives and the general sequence of events that comprise the experiment, an introductory briefing will be prepared and presented as the first activity at each site. At this time, any questions that management or personnel at the maintenance facility have concerning this experiment or its implementation will be addressed.

Site Preparation

Site preparation consists of all of the activities necessary from the time of arrival of the equipment and personnel to the time when the maintenance facility's inspectors are ready to initiate the experiment. As noted in Table 3-1, the major activities consist of receiving the equipment, assembling of the mounting fixture, mounting specimens on the mounting fixture, and performing any necessary pre-test instrumentation calibration. All of the activities performed in the site preparation area will be performed by the two monitors.

Experiment Performer's Briefing

At each site, the maintenance facility's inspectors participating in the experiment will be given an overview briefing. This briefing will outline the experiment, review the protocol, and ensure that the inspector understands what he/she has to do to implement the experiment. In addition, there will be a pre-test interview/discussion. Some of the human factors related to the performing of this experiment clearly involve experience, training, etc., for each inspector. This type of information will be gleaned during the pre-test interview.

Experiment Implementation

The actual experiment will be performed at this point in the sequence. Prior to inspections of the test samples, the NDI monitor will characterize the reference standards used in each facility against a master calibration block. The recording of conditions as noted in Table 3-1 will be done by the monitors. Equipment identification recording will be a joint activity between the inspectors and the monitors. The inspection sequence on the test samples will be performed by the inspection team in accordance with the site's basic inspection procedures, and using the site's inspection tools and test equipment. A major role of the monitors is to observe this process and to highlight significant activities that are related to the human factors elements. These factors, in the performance of the inspections, will be recorded in accordance with the observation protocol. For each site multiple inspections will be performed by different inspectors (with one repeat trial - same inspector). Recording conditions, identifying equipment, and recording observations will be done for each of the replications of the experiment.

Post Experiment Efforts

When the experiments are completed, the set of activities shown in Table 3-1 will be performed. The first item, Post Experiment Interviews of Performers, provides the final sets of "data" related to the experiments. The rest of the activities listed under post experiment efforts are directed towards the tear down of the experimental set-up and the preparation for moving the experimental set-up to the next site. The final item, Debrief Site Management, is designed to ensure that good communications are maintained with the maintenance site management personnel concerning the experiments and the interaction with the inspection crew.

3.3 Data Qualification

A significant element in all well-run experiments is the implementation of a process to ensure that all of the required data has been acquired, that all of the data are "good" data, and that all data are properly identified and marked. The activities shown in Table 3-1, under Data Qualification, address these areas.

The data sets will be marked at the completion of each experimental run. The observation information compiled in accordance with protocol will be prepared subsequent to the completion of each run, and will be carefully identified as to date, inspector, and shift to ensure proper correlation. At the completion of each run, the set of raw data will be examined to ensure that all required sets of information have been taken. A significant part of this activity is to review all of the forms required by the protocol, to ensure that all elements of data required by the forms have been addressed and thoroughly documented. If the records are handwritten, legibility is a key issue. (The current approach anticipates using notebook computers with preprogrammed forms to ensure legibility and easy translation of the data into a summary data base.)

Finally, a quick review by the human factors expert and the NDI specialist immediately after the run to ensure that no anomalous or obviously inconsistent sets of results are contained in the data is worthwhile. Misunderstandings can be cleared up immediately if the test set-up and the people who are performing the inspections are still in place. Similarly, an improperly implemented element of the protocol can be dealt with while the test set-up is still in place.

The data qualification activity is not designed to analyze the results or to attempt to draw conclusions concerning the interpretation of the data. Rather, it is designed to ensure that all of the data needed by the analysts are clearly, correctly, and accurately accumulated in the process of performing the experiment.

Table 3-1. Experiment implementation elements.

Major Element	Key Factors	Activities
Preparation	Monitor Assignment	• Selection • Alternates • Training/Familiarization
	Site Coordination	• Final Selection • Scheduling • Alternate Site Identification
	Safety	• Review of OSHA Requirements • Preliminary Hazards Analysis • Cosideration of Site Unique Safety Elements
	Sample Acquisition	• Receipt • Identification • Pre-experiment Characterization
	Test Equipment Acquisition	• Receipt • Calibration • Checkout
	Shipping and Handling	• Containers • Transportation • Handling Equipment
	Experiment Integration	• Integration of Samples and Containers • Integration of Samples and Frame • Trial Runs of Protocols and Documentation • Baseline Data Acquisition
	Dress Rehearsal	• Briefing Observers • Experiment Execution • Debriefing by Observers
	Storage	• Samples • Frame (Mounting Fixture) • Test Equipment • Data
Execution	Site Introduction	• Briefing
	Site Preparation	• Receipt of Equipment • Movement to Experiment Area • Unpacking • Inspection • Frame Assembly • Sample Mounting • Pretest Instrument Calibration • Gage Block "Calibration" • Monitoring Instrument Checkout

Table 3-1. Experiment implementation elements (cont.)

	Inspectors Briefing	• Overview Briefing • Pretest Interview/Discussion
	Experiment Implementation	• Reference Standards Experiment • Recording of Condition • Temperature • Humidity • Lighting • Noise • General Operating Conditions • Equipment Identification Recording • Make and Model • Serial Number • Condition (calibration, etc.) • Perform Inspection Sequence on Samples • Record Observations per Protocol • Repeat Inspection Sequence as Required by Protocols
	Post Experiment Efforts	• Post Experiment Interview of Inspectors • Disasembly of Frame/Sample Assembly • Inspection of Specimens • Refurbishment as Required • Pack and Prepare for Shipment • Ship to Next Site • Aggregate and Ship Data • Debrief Site Management
Data Qualification	Identification of all Data Sets	• Marking • Correlation (Data, Observations, Records, etc.)
	Complete Data Set Determination	• All Raw Data Taken • All Forms Completed as Required by Protocol • All Entries Completed as Required by Protocol • All Data Legible
	Quality Check	• Results Reasonable (Quick Look Evaluation)

4. Expected Results and Data Analysis

An outline of the planned data analysis was given in Section 2.4. This section discusses in more detail how the data are to be stored, made available, and presented. The types of analysis needed can be performed by various commercially available software packages. Specifically, the SAS software for statistical analysis is available.

In a reliability assessment program that entails visiting many facilities, it is important that data analysis activities be done in parallel with gathering the data. Inspection results will be taken from the tape on which they are recorded and will be transferred to an electronic data base. The transfer to an electronic data base will be done in timely manner so that preliminary data analysis can take place. This preliminary data analysis can give indications of problems. For example, an unflawed site consistently being flagged as a flaw could indicate changes in the specimen.

The transcription of hard copy inspection results to the electronic data base will likely occur in the field. Both the electronic data base and the hard copy will then be sent (under separate cover) to Sandia where preliminary analysis will be done. On-site analysis of inspection data by the personnel who will be monitoring the experiment will not be done. This is to assure that flaw information is not available at the inspection sites.

For summary presentations, individual POD curves for each inspector will be shown on one plot. The total variation due to inspectors will be visually apparent. Similarly, POD curves will be fit to the inspection results averaged across inspectors within a facility. A plot will be made with individual curves representing each facility. The result is a visual presentation of facility variation.

Plots showing inspector-to-inspector and facility-to-facility variation are fundamental. However, the significance of the observed variation depends on factors of the experimental design, including the number of flaws inspected and the number of inspections. The statistical significance will be assessed and reported.

Individual ROC curves will also be displayed on the same plot. Similarly, aggregated ROC curves by facility will also be put on a single plot. Thus, the same variation sources as discussed for the POD analysis will be displayed in the ROC presentations. In addition, the ROC curves derived when constrained to specified ranges of crack length will be constructed and displayed on the same plot. This will give a visual presentation of the relationship between the ROC curve and crack length.

The results of ANOVA and MANOVA analyses on the α's and β's from individual POD fits and interpretations of the ROC measures, such as the "A" index, will also be part of the basic reporting. The primary explanatory variables included in these analyses will be those that were controlled. However, exploratory analysis will be pursued using various observed conditions as possible explanatory factors.

An experiment, such as this one, that obtains data from many facilities, industry wide, will generate much interest. It is important to make the full dataset of inspection results available for general distribution. This will result in independent analyses and will facilitate open discussion of the results. Therefore, a data base description document will be prepared. A PC-based flat ASCII file will be made available along with the data base documentation for those requesting the data.

5. Preliminary Action Plan

The main efforts of any reliability assessment experiment are spent in planning, implementing, analyzing, determining POD estimates, and producing the final report. The process, however, is not complete until the initial goals of the program have been reviewed and compared with the program results. Normally, this is accomplished by making a list of recommendations, reaching certain conclusions, and recommending what elements require further investigation.

During the course of conducting the reliability assessment experiment, a great deal of information will be collected and analyzed. Based on the data collected, it is not unlikely that certain courses of action can be recommended that could have an impact on the overall inspection process and improve its reliability. A Preliminary Action Plan will be determined, based on the lessons learned and the data collected while conducting the experiment.

This plan will consider, but not be limited to, actions pertaining to such inspection aspects as:

- Standardized calibration techniques for equipment, sensors, and calibration blocks
- Inspector training programs
- Standardized certification examinations
- Re-examinations
- Improvements in environmental conditions
- Improvements in staging
- Improvements in fixtures
- More meaningful data collection

Based on the information available, methods for implementing identified concerns will be determined.

The benefits of action based on reliable inspection data are manifold. They should lead to increased confidence in inspection, giving greater passenger confidence. By identifying the key reliability issues, maintenance procedures can be optimized to improve performance at minimum cost and inspection staff can gain a greater understanding of their own jobs. The result will be a more productive maintenance organization with inspectors having the necessary resources and support to better perform their job.

References

1. Spencer, Borgonovi, Roach, Schurman, and Smith, "Reliability Assessment at Airline Inspection Facilities, Vol. I: A Generic Protocol for Inspection Reliability Experiments," DOT/FAA/CT-92/12,I

2. National Transportation Safety Board, Aircraft Accident Report, NTSB/AAR 89/03, 1988.

3. Boeing Quality Control Research and Development Report PE 373A-1, "Reliability of Eddy Current Lap Splice Inspection Procedures, May 1991.

4. T. Swift, National Resource Specialist, Fracture Mechanics/Metallurgy, Information: Multi-Site Damage, FAA Memorandum to Manager, Aircraft Engineering Division AIR-100, January 3, 1991.

5. Boeing Commercial Airplane Group, "Contract Maintenance Service Availability for Commercial Aircraft", D6-55339, 1991.

6. G. Samavedam and D. Hoadley, "Fracture and Fatigue Strength Evaluation of Multiple Site Damaged Aircraft Fuselages - Curved Panel Testing and Analysis", Foster-Miller Report No. DTS-9024, May 1991.

APPENDIX A

PROTOCOLS

LIST OF FIGURES

This appendix gives more information on the requirements for the monitor's protocols and examples of draft data sheets and briefing materials. These protocols will be completed before the dress rehearsal and modified if necessary in light of the performance during those trials.

Experimental Plan

This document will present the overall program and its objectives and methodology. It will also include the detailed schedule, hardware descriptions and identification system (for panels and specimens), and other pertinent information from the implementation section of this document.

Start-Up Procedures

A checklist of the hardware, materials, inspection procedures, log books, experimental orders and plan for the day.

Panel Layout Diagrams

These diagrams will provide the designs for specimen placement for each research run. The specimens and panels will be identified by serial number and location, in order, from a starting end for each lap splice.

Briefing

This document will present the standard introduction given to the inspectors including an explanation of the research, confidentiality safeguards, and agreement to participate. A separate briefing will be given to the facility management.

Reference Standards Experiment

This will detail the procedure for carrying out, by the monitor, the reference standards experiment. It will be based on the calibration section of the Boeing 737 inspection procedure.

Pre-Trial Question List

This checklist will help the monitors gather necessary background information and demographic information about the inspectors before they begin the trial.

Inspector Supervision Procedures

This document will describe the aim and requirements of the inspectors from the monitor's point of view. It will provide guidance to the monitors on how to proceed under particular circumstances.

Trial Checklist

This checklist will give the actions to be taken by the monitor during the inspections (e.g., filling in questionnaires and recording relevant data defined above). A summary of environmental factors and inspection data that are to be recorded is shown in the Facilities Characteristics Checklist, attached.

Data Recording/Transfer Procedures

The procedure for transferring records of the inspector's work will be provided in this document. An outline is given on the Data Recording Form, attached. Current recommendations are that the inspector marks his findings on the specimens and panels and that these are then transferred by the monitor to the data base. The checklists will be recorded directly to the data base. A check procedure for transfer accuracy will be included.

Close-Down

This document will describe the methods for filing paperwork, computer disks, etc., at the end of a session. It will also provide steps for dismantling, storing, and shipping the hardware. A checklist will be provided for ensuring that all equipment, data, and forms are properly packed and labeled.

End of Trial Debriefing

This is the post-experiment questionnaire which the monitor will complete in consultation with the inspector in order to determine both the inspector's attitudes to and opinions of the trial and how he/she is feeling. A draft structure of the interview is given on the Outbriefing Questions for Inspectors form, attached. A separate debriefing will be given to the management to thank them and give general overview of how the trials proceeded. No specific inspection or personnel data will be disclosed.

Hangar Size_______________

LIGHTING -

Artificial ____ Outdoors ____

____ Glaring
____ Bright
____ Average
____ Dim
____ Shadowed

TEMPERATURE -

____ Cold & Drafty
____ Cold
____ Comfortable
____ Hot
____ Very Hot
____ Hot & Humid

____ Light meter reading (foot-candles) at time of inspection

GENERAL ATMOSPHERE -

____ Gloomy
____ High-pressured
____ Noisy (see below)
____ Cheerful
____ Quiet
____ Relaxed

MANAGEMENT -

High pressure? (describe)
Schedule constraints? (describe)
Describe intercommunications
Team cohesion? (describe)
Distracting tasks? (describe)

TOOLS -

Availability? (describe) ____ Clean?
Employee furnished? (describe)
Adequate? (describe)
Calibrated? (describe)

HOUSEKEEPING -

____ Neat?
____ Well organized?
____ Describe unusual characteristics (unusually good or bad)

INSPECTOR -

Physical condition (describe)
Attentiveness (describe)
Age
Sex

NOISE -

____ Steady level
____ Intermittent
____ High
____ Low
____ Noise meter reading (dB)

Figure A-1. Facility Characteristics Checklist

Eddy Current Data Sheet
Monitor collects with each inspection.

Date: ________________
Inspector ID:__________

Layout for design ___________
System Operating Ambient Temperature _______________________
State other equipment environmental constraints ________________________
____

Test Frequency ____ Scan Speed _____ Filtering
Horizontal Gain ____ Vertical Gain ____ Lift-off technique
Coil Output Impedance

Probe

Contact ____________ Noncontact _________
Differential ________ Absolute __________ Others ___________
Pancake ____________ Toroid Coil _________ Others ___________
Coil Diameter _______ Shielding __________

Scanning Technique ________________ Digitization _______________
Calibration Level ________________ Inspection Threshold _______________
Calibration on paint/unpainted ____ (tape)

Attach a sketch of the inspection set-up. Include part orientation with respect to flaw orientation and eddy current direction.

Describe technique for analyzing, rejecting and recording a defect signal or affix procedure used.

Describe deviations from procedure.

Figure A-1. Facility Characteristics Checklist (cont.)

DESIGN

The form will have heading spaces and three columns for each inspector. The following will be recorded in the heading spaces

- Code Designation
- Date
- Start Time
- End Time
- Equipment used (type, cables, probes, calibration standard) [see the Facilities Characteristics Checklist for eddy current specific form]

The columns will be:

- Crack response (Y/N) [this data transferred from fuselage]
- Confidence rating
  (1 = very sure, 2 = pretty sure,
  3 = some justification)

- Comments: It is very important to record break start and stop times and any other information that would help in interpreting the data later on, for example, repeated inspections.

Figure A-2. Data Recording Form

NOTE: READ ESSENTIALLY AS WRITTEN, AFTER EXPLAINING THAT WE NEED SOME INFORMATION THAT WE COULD USE TO IMPROVE THIS EXPERIMENT.

1. How much was working on the test piece like working on an aircraft?

_____	Very
_____	Somewhat
_____	Similar in some ways, not in others
_____	Somewhat dissimilar
_____	Very dissimilar
_____	Not at all similar

2. What are the major differences that you feel are important? (Pick the three most major.)
   a.

   b.

   c.

3. How would you suggest that we improve this research?

4. How much did the watcher bother you?

_____	A lot
_____	Some
_____	Not at all

5. How often have you done this job of crack detection?

6. How long has it been since you last did this job of crack detection?

7. How much training have you had on this equipment?

8. What do you think the priority of NDI is compared to the other things that you need to do?

   - To you personally:

   - To your management:

Figure A-3. Outbriefing Questions for Inspectors

APPENDIX B

SPECIMEN DESIGN AND MANUFACTURE

LIST OF FIGURES

A brief description of the generation of the flaws as well as the frame design is given in this appendix.

Small Specimens

The cracked upper plates will be produced as follows:

1. An oversized "upper plate" will be placed in a mechanical test machine (Figure B-1). Undersized holes will be pre-drilled at the locations where the cracks are to be propagated. Since fatigue cracks normally grow in the direction perpendicular to the load, off-angle cracks will be produced by setting up the tensile test in the manner depicted in Figure B-2. Increasing either the width or height of the panel specimen will greatly increase the plate size required to generate off-angle cracks.

2. Crack starters will be sequentially placed in these holes - using crack growth information for 2024-T3 aluminum - to achieve the desired crack distribution. Any means that is used to initiate the cracks will be eliminated from the final specimen. Figure B-3 shows how this is accomplished where a crack starter notch is removed when the final 5/32-in. diameter hole is drilled.

3. Sample plate flaw specifications are shown in Figure B-4. Although exact crack lengths are given, limitations in fatigue growth will not allow all of the cracks to have the desired lengths. Rather, the cracks will be sequentially initiated in an attempt to produce the desired length distribution. The longest crack on each particular plate will be used as the controlling factor. When it has been reached, the loading will cease and all of the existing cracks will be measured. At that point, it will be determined if continued loading will produce a better crack distribution. This iterative process will be carried out during the production of each cracked upper plate.

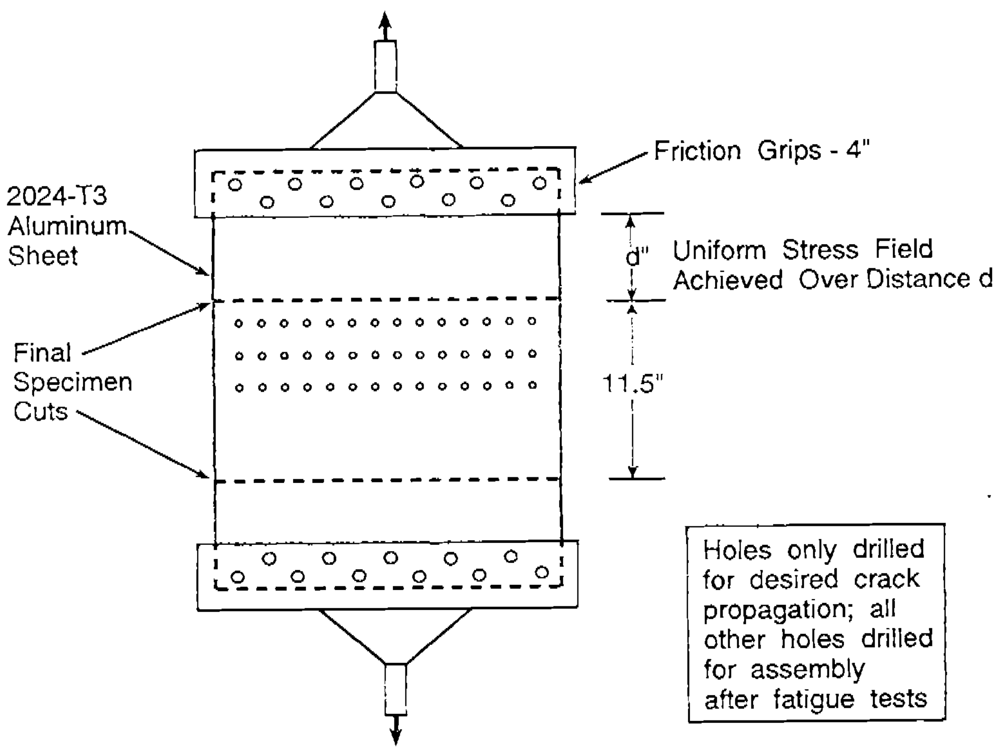


Figure B-1. Fatigue loading for crack propagation in upper plate.

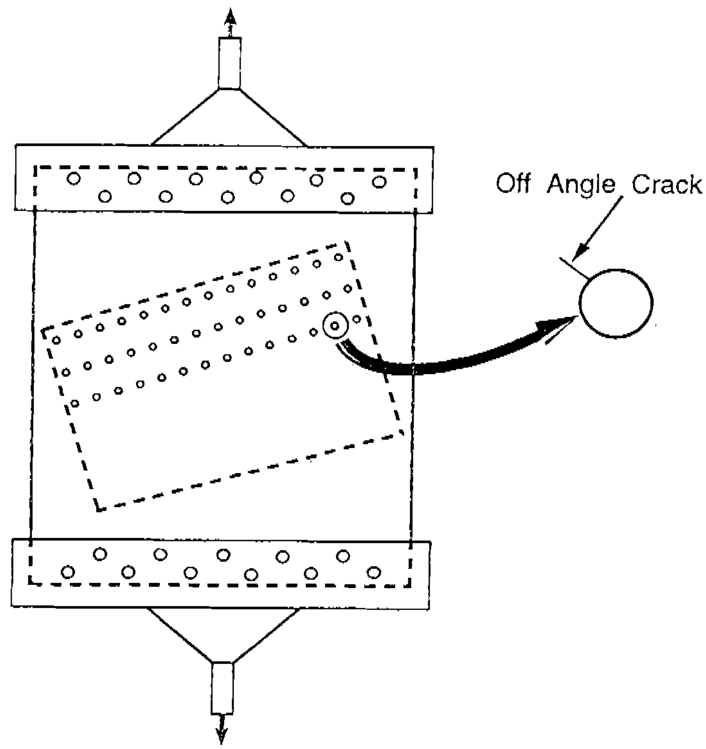


Figure B-2. Tensile test setup used to produce off angle cracks.

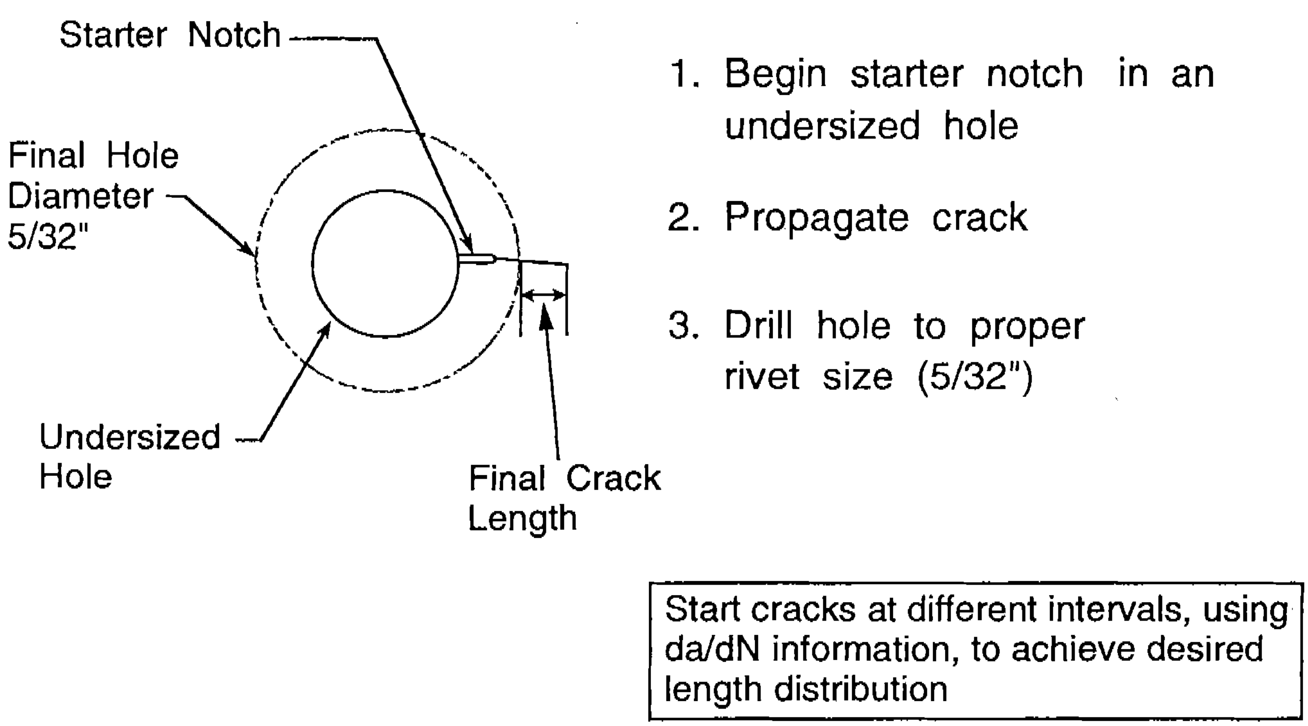
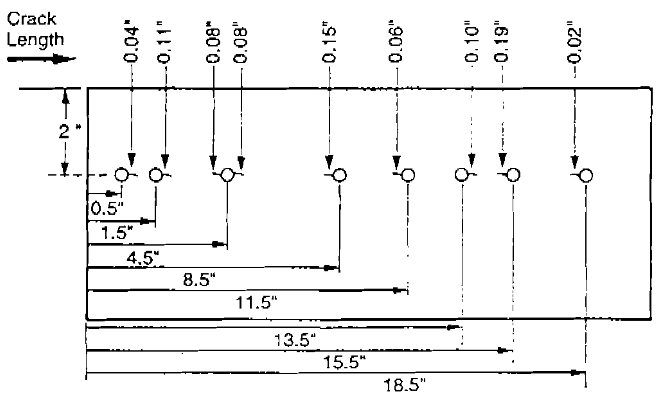


Figure B-3. Elimination of crack starter notch.

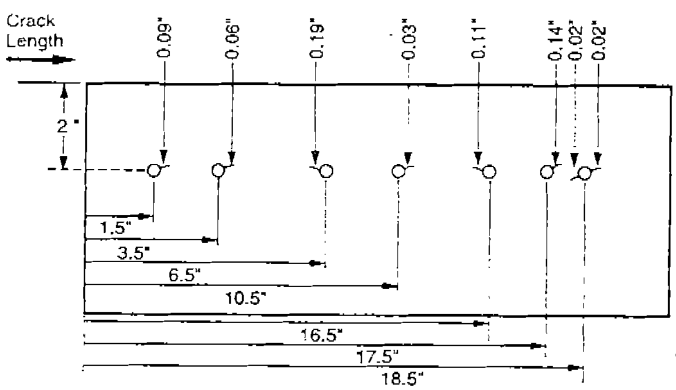
After the cracked upper plates have been produced, this plate will be riveted into the final panel specimen shown in Figure B-1. This task involves drilling all remaining rivet holes and associated counterbores. This assembly procedure will adhere to aviation specifications in general and to the Boeing specifications where applicable.

Proof-of-Concept Demonstration Plates. To deliver a tangible proof-of-concept, the AANC had two sets of demonstration plates fabricated. Two candidate companies were chosen to produce these demonstration plates. Figure B-4 shows the crack distribution specifications of the two test specimen upper plates. Both companies were able to do a reasonable job of meeting the specifications.



1. All hole location tolerances are ± 0.003" in both directions
2. All crack length tolerances are ± 0.005"; cracks emanate from right side, left side, or both sides as shown in drawing
3. Final hole diameter is 5/32" ± 0.002"
4. All cracks are along hole line (angle = 0°)

DEMONSTRATION PLATE #1



1. All hole location tolerances are ± 0.003" in both directions
2. All crack length tolerances are ± 0.005"; cracks emanate from right side, left side, or both sides as shown in drawing
3. Final hole diameter is 5/32" ± 0.002"
4. All cracks are off angle (angle = 22°)

DEMONSTRATION PLATE #2

Figure B-4. Demonstration Plates 1 and 2. Hole locations are ± .003 inch. All cracks on plate 1 are horizontal. All cracks on plate 2 are off angle (22° from horizontal).

Aircraft Test Panel

Figure B-5 shows a mechanical drawing of the larger panel. The planform dimensions, which include the connection flanges for the load frame, are 10 ft long by 6 ft high. The stringer spacing is an adjustable variable and panels produced to date have had either 8-in. or 9.6-in. stringer spacing. The splice is joined by three longitudinal rivet rows; the center rivet row also attaches the skin to a stringer. One-inch wide tear straps are positioned in the hoop direction on 20 inch centers at each frame. The frames are attached to the skin in each stringer bay by a fabricated angle shear-clip. All through-skin rivets are 5/32-in. diameter, low profile, shear head 100-degree countersink rivets. Photographs of typical panels are shown in Figure 2-2. The panels are fabricated by East Coast Aero Tech, Hanscom Field, MA, under the supervision of Foster-Miller.

Load Frame Design. This load frame applies simultaneous internal pressure (hoop load) and longitudinal loads to the curved segment of stiffened aircraft panel. Figures B-6 and B-7 are photographs of the entire test facility. This test fixture was designed to include the following features:

1. Fixture to panel connections reproduce conditions of full-circle fuselage.
2. Panel loadings simulate normal pressurization loads in the panel. The load is proportioned to produce an axial stress of half of the hoop stress because of the internal pressure, as it exists in the full-scale round aircraft fuselage; proper phasing of these loads is also maintained.
3. Providing cyclic pressurization loads.
4. Loading the panel to a pressure equivalent to one-half the panel's ultimate capacity.

The general approach to panel testing (i.e., generating flaws in the panels) is to anchor two long sides and one end of the panel to the fixture. Panel loading is achieved by pulling on one curved end and pressure loading the panel on its concave side by pressurized water. The pressure load is contained by the fixture, by an inflatable seal between the fixture and the panel, and by the panel. Figure B-8 is a schematic of the panel mounted in the test fixture.

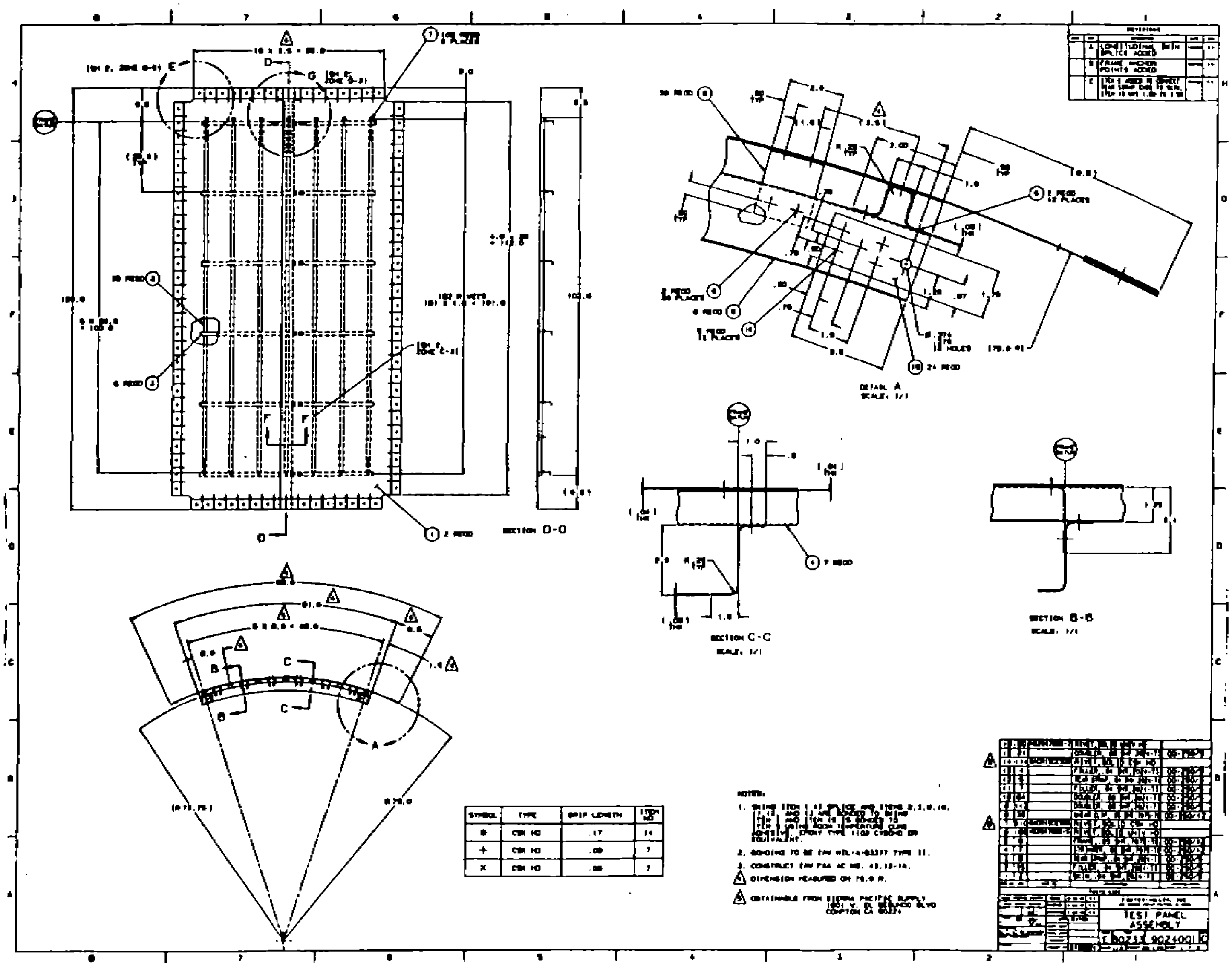


Figure B-5. Full-scale test panel built by Foster-Miller.

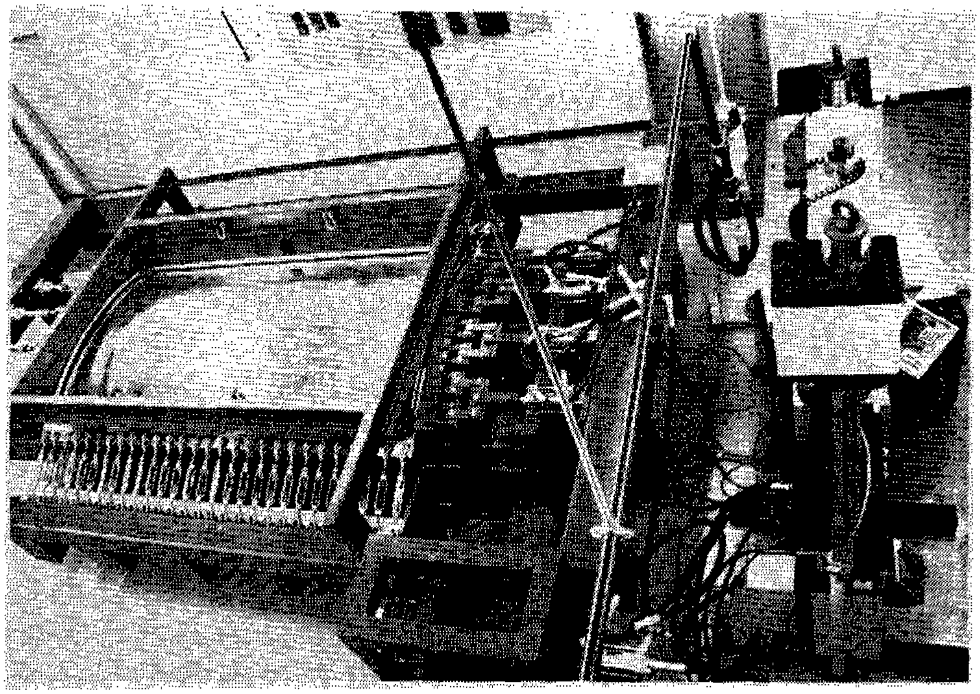


Figure B-6. Full-scale panel test facility

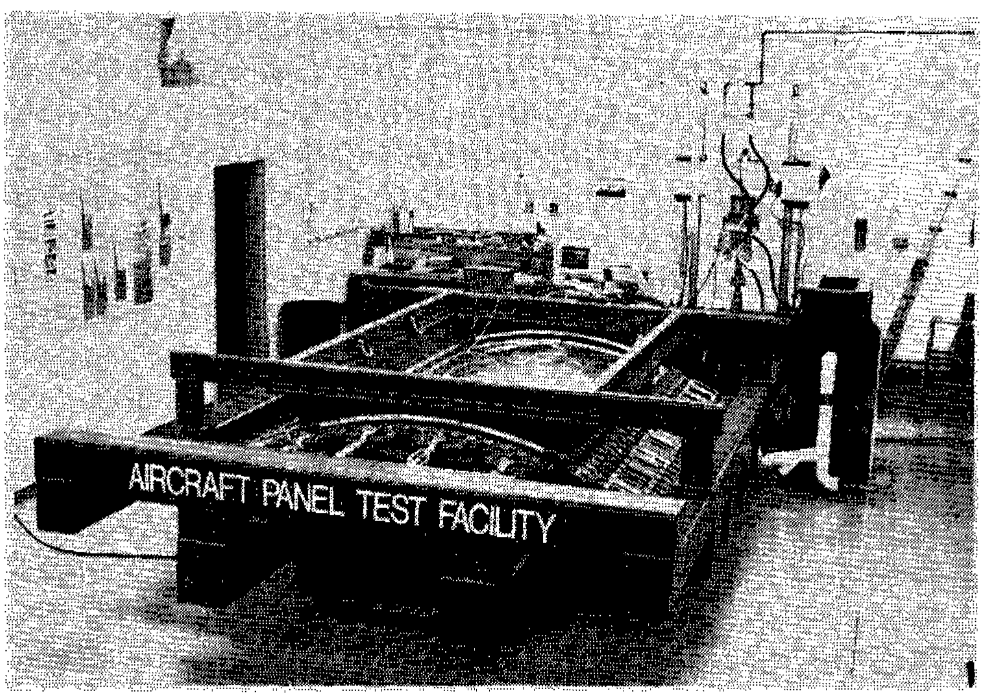


Figure B-7. Panel test frame structure

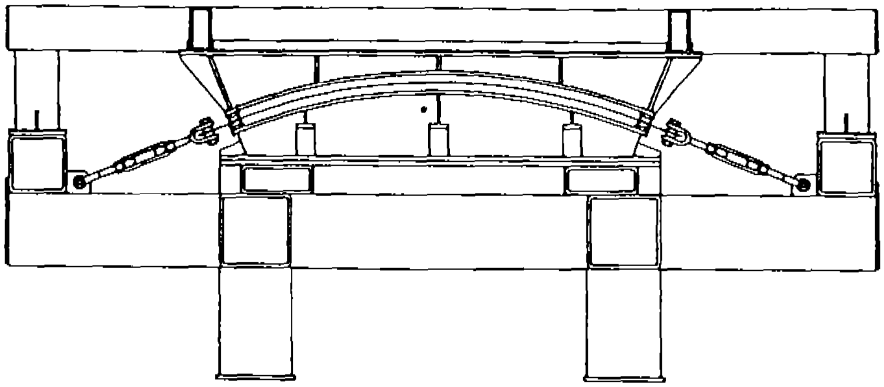


Figure B-8. Panel installation in test fixture.

Test Frame/Support Structure

Test Frame Sections. For shipping and handling purposes, the test frame breaks down into 10-ft or 5-ft sections. The sections which support the small test specimens will have a substructure to provide stability and specimen mounting features. Figure B-9 shows the substructure or skeleton of a typical 10-ft section. A 5-ft section would be similar. It will be fabricated from square aluminum tubing assembled to mimic an aircraft structure of stringers and ribs. The frame sections will be rolled to the 75 inch radius found on Boeing aircraft. The entire substructure will be assembled into a single unit by either welding the structural members together or by using a structural adhesive. Once assembled, each 5-ft section will weigh approximately 50 lbs.

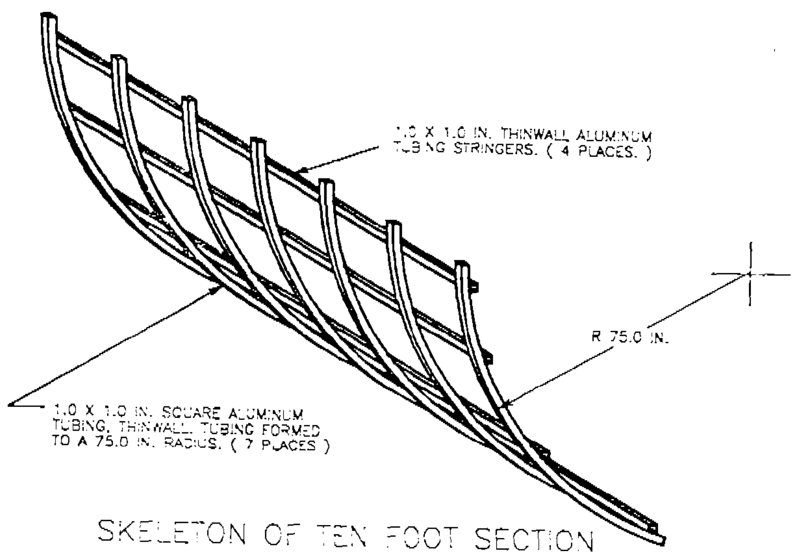


Figure B-9. Substructure of support frame for small test specimens.

Fuselage Skin. The test frame will be entirely covered with a thin aluminum skin. Figure B-10 shows the resulting assembly. The upper and lower portions of the skin are formed by the test specimens that are mounted into two separate lap joint inspection rows. The rows will be aligned to match the lap joint inspections at stringers 14 and 19 on the Boeing 737. An aluminum skin of comparable thickness will be used to fill the gap between the two lap splice inspection rows. All three substructures used to mount the 20-in. test specimens will be packed in a single shipping crate.

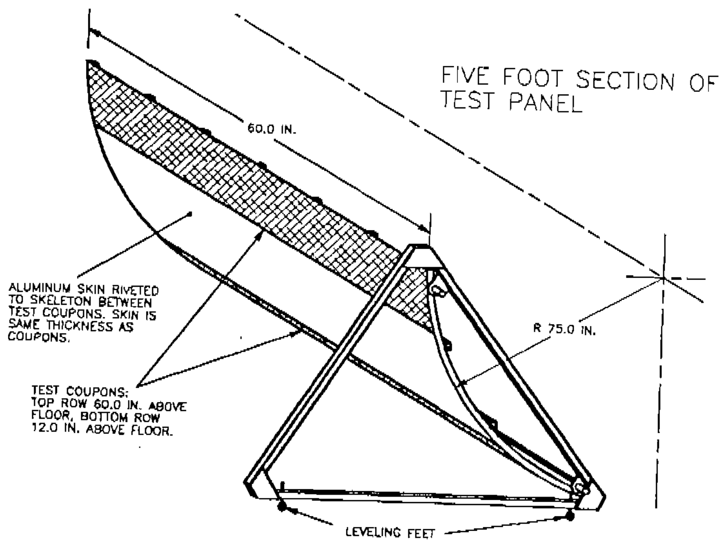


Figure B-10. Assembly of five-foot test section with test specimen and end supports.

End Supports. Triangular supports will be placed at the ends of each section. A single triangular end support is shown in Figure B-10. The three structural beams (sides of the triangle) will be hinged at the apices. The hinges will feature a pin arrangement that allows the length of each side to be individually adjusted. This way, the overall height of the frame and/or the angle of the fuselage section can be changed; thus, the frame can be reused for different experiments. The triangular supports will be sized to allow the inspector to walk through them. Thus, he/she can travel the entire length of the longitudinal lap splice joint without leaving the inspection surface. To provide sufficient clearance for the inspector to walk the length of the frame, it may be necessary to include an additional short leg at the apex of the triangle. Figure B-11 shows the resulting "dog-leg" assembly on the end support, as well as how the angle and height of the inspection area can be adjusted using this frame design. One final feature of note is the use of leveling feet to allow for frame assembly on uneven floors. All of the triangular supports (six or seven required for this experiment) can be dismantled and placed in one shipping crate.

Mounting the Substructures and Linking them Together. Individual sections will be connected to the triangular end supports by using aluminum round stock as metal dowels (see Figure B-10). They will slide into the square aluminum tubing and will be pinned into place. These round bars also serve the dual purpose of connecting the fuselage sections into a single fuselage segment. Figure B-12 shows the complete assembly with the test specimens in one frame and the Foster-Miller panels in another. The handling fixtures that are currently used on the full-size, Foster-Miller panels will be modified as necessary to conform to this set-up.

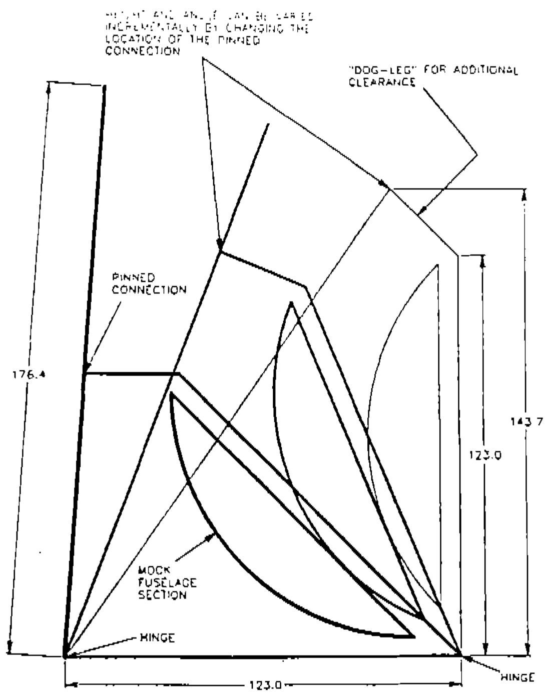


Figure B-11. Variation in end support assembly to incrementally adjust height and angle of inspection surface

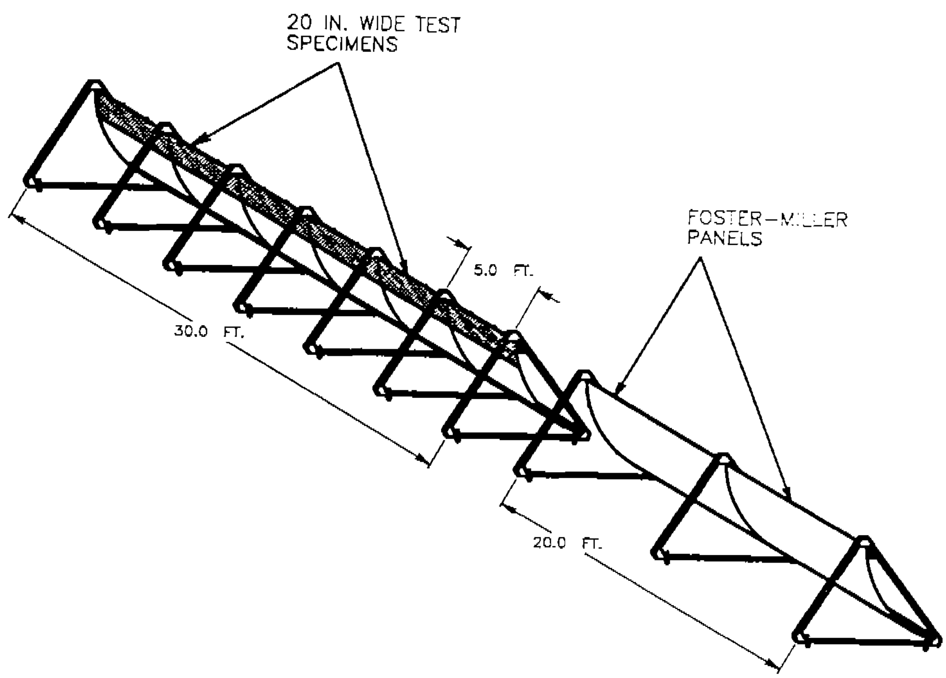


Figure B-12. Experimental test setup

Test Specimen Mounting. The method used to mount the 20-in. wide test panels to the substructure sections allows for quick and easy placement and provides the ability to achieve accurate alignment of the lap splice rows. The frame is designed such that the specimens clip into place. The clips run along the upper and lower edges of the specimens. The resulting specimen attachment is shown in Figure B-13.

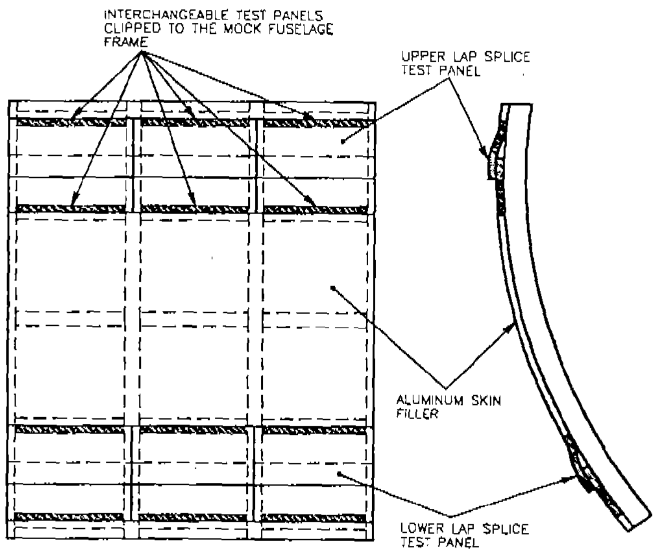


Figure B-13. Test specimen mounting to mock fuselage frame.

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